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Scientific Investigations Report 2012–5049

U.S. Department of the Interior
U.S. Geological Survey

Cover. Agricultural activity overlying the Valley and Ridge Physiographic Province carbonate-rock aquifer, typical of eastern agriculture (left). Center-pivot irrigation in the Central Columbia Plateau in Washington State, typical of western irrigated agriculture (center). Snow plow applying deicing chemicals (right). Photo of agricultural activity ©iStockphoto/diane39. Photo of center-pivot irrigation by Doug Wilson, Agricultural Research Service. Photo of snow plow ©iStockphoto/PrairieArtProject.

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By Bruce D. Lindsey and Michael G. Rupert

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U.S. Geological Survey
Marcia K. McNutt, Director

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Foreword

The U.S. Geological Survey (USGS) is committed to providing the Nation with reliable scientific information that helps to enhance and protect the overall quality of life and that facilitates effective management of water, biological, energy, and mineral resources (*http://www.usgs.gov/*). Information on the Nation's water resources is critical to ensuring long-term availability of water that is safe for drinking and recreation and is suitable for industry, irrigation, and fish and wildlife. Population growth and increasing demands for water make the availability of that water, measured in terms of quantity and quality, even more essential to the long-term sustainability of our communities and ecosystems.

The USGS implemented the National Water-Quality Assessment (NAWQA) Program in 1991 to support national, regional, State, and local information needs and decisions related to water-quality management and policy (*http://water.usgs.gov/nawqa*). The NAWQA Program is designed to answer: What is the quality of our Nation's streams and groundwater? How are conditions changing over time? How do natural features and human activities affect the quality of streams and groundwater, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues and priorities. From 1991 to 2001, the NAWQA Program completed interdisciplinary assessments and established a baseline understanding of water-quality conditions in 51 of the Nation's river basins and aquifers, referred to as Study Units (*http://water.usgs.gov/nawqa/studies/study_units.html*).

In the second decade of the Program (2001–2012), a major focus is on regional assessments of water-quality conditions and trends. These regional assessments are based on major river basins and principal aquifers, which encompass larger regions of the country than the Study Units. Regional assessments extend the findings in the Study Units by filling critical gaps in characterizing the quality of surface water and groundwater, and by determining water-quality status and trends at sites that have been consistently monitored for more than a decade. In addition, the regional assessments continue to build an understanding of how natural features and human activities affect water quality. Many of the regional assessments employ modeling and other scientific tools, developed on the basis of data collected at individual sites, to help extend knowledge of water quality to unmonitored, yet comparable areas within the regions. The models thereby enhance the value of our existing data and our understanding of the hydrologic system. In addition, the models are useful in evaluating various resource-management scenarios and in predicting how our actions, such as reducing or managing nonpoint and point sources of contamination, land conversion, and altering flow and (or) pumping regimes, are likely to affect water conditions within a region.

Other activities planned during the second decade include continuing national syntheses of information on pesticides, volatile organic compounds (VOCs), nutrients, trace elements, and aquatic ecology; and continuing national topical studies on the fate of agricultural chemicals, effects of urbanization on stream ecosystems, bioaccumulation of mercury in stream ecosystems, effects of nutrient enrichment on stream ecosystems, and transport of contaminants to public-supply wells.

The USGS aims to disseminate credible, timely, and relevant science information to address practical and effective water-resource management and strategies that protect and restore water quality. We hope this NAWQA publication will provide you with insights and information to meet your needs, and will foster increased citizen awareness and involvement in the protection and restoration of our Nation's waters.

The USGS recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for cost-effective management, regulation, and conservation of our Nation's water resources. The NAWQA Program, therefore, depends on advice and information from other agencies—Federal, State, regional, interstate, Tribal, and local—as well as nongovernmental organizations, industry, academia, and other stakeholder groups. Your assistance and suggestions are greatly appreciated.

William H. Werkheiser
USGS Associate Director for Water

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Volume	
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
liter (L)	61.02	cubic inch (in^3)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Methods for Evaluating Temporal Groundwater Quality Data and Results of Decadal-Scale Changes in Chloride, Dissolved Solids, and Nitrate Concentrations in Groundwater in the United States, 1988–2010

By Bruce D. Lindsey and Michael G. Rupert

Abstract

Decadal-scale changes in groundwater quality were evaluated by the U.S. Geological Survey National Water-Quality Assessment (NAWQA) Program. Samples of groundwater collected from wells during 1988–2000—a first sampling event representing the decade ending the 20th century—were compared on a pair-wise basis to samples from the same wells collected during 2001–2010—a second sampling event representing the decade beginning the 21st century. The data set consists of samples from 1,235 wells in 56 well networks, representing major aquifers and urban and agricultural land-use areas, with analytical results for chloride, dissolved solids, and nitrate. Statistical analysis was done on a network basis rather than by individual wells. Although spanning slightly more or less than a 10-year period, the two-sample comparison between the first and second sampling events is referred to as an analysis of decadal-scale change based on a step-trend analysis.

The 22 principal aquifers represented by these 56 networks account for nearly 80 percent of the estimated withdrawals of groundwater used for drinking-water supply in the Nation. Well networks where decadal-scale changes in concentrations were statistically significant were identified using the Wilcoxon-Pratt signed-rank test. For the statistical analysis of chloride, dissolved solids, and nitrate concentrations at the network level, more than half revealed no statistically significant change over the decadal period. However, for networks that had statistically significant changes, increased concentrations outnumbered decreased concentrations by a large margin. Statistically significant increases of chloride concentrations were identified for 43 percent of 56 networks. Dissolved solids concentrations increased significantly in 41 percent of the 54 networks with dissolved solids data, and nitrate concentrations increased significantly in 23 percent of 56 networks. At least one of the three—chloride, dissolved solids, or nitrate—had a statistically significant increase in concentration in 66 percent of the networks. Statistically significant decreases in concentrations were identified in 4 percent of the networks for chloride, 2 percent of the networks for dissolved solids, and 9 percent of the networks for nitrate. A larger percentage of urban land-use networks had statistically significant increases in chloride, dissolved solids, and nitrate concentrations than agricultural land-use networks.

In order to assess the magnitude of statistically significant changes, the median of the differences between constituent concentrations from the first full-network sampling event and those from the second full-network sampling event was calculated using the Turnbull method. The largest median decadal increases in chloride concentrations were in networks in the Upper Illinois River Basin (67 mg/L) and in the New England Coastal Basins (34 mg/L), whereas the largest median decadal decrease in chloride concentrations was in the Upper Snake River Basin (1 mg/L). The largest median decadal increases in dissolved solids concentrations were in networks in the Rio Grande Valley (260 mg/L) and the Upper Illinois River Basin (160 mg/L). The largest median decadal decrease in dissolved solids concentrations was in the Apalachicola-Chattahoochee-Flint River Basin (6.0 mg/L). The largest median decadal increases in nitrate as nitrogen (N) concentrations were in networks in the South Platte River Basin (2.0 mg/L as N) and the San Joaquin-Tulare Basins (1.0 mg/L as N). The largest median decadal decrease in nitrate concentrations was in the Santee River Basin and Coastal Drainages (0.63 mg/L). The magnitude of change in networks with statistically significant increases typically was much larger than the magnitude of change in networks with statistically significant decreases. The magnitude of change was greatest for chloride in the urban land-use networks and greatest for dissolved solids and nitrate in the agricultural land-use networks. Analysis of data from all networks combined indicated statistically significant increases for chloride, dissolved solids, and nitrate.

Although chloride, dissolved solids, and nitrate concentrations were typically less than the drinking-water standards and guidelines, a statistical test was used to determine whether

or not the proportion of samples exceeding the drinking-water standard or guideline changed significantly between the first and second full-network sampling events. The proportion of samples exceeding the U.S. Environmental Protection Agency (USEPA) Secondary Maximum Contaminant Level for dissolved solids (500 milligrams per liter) increased significantly between the first and second full-network sampling events when evaluating all networks combined at the national level. Also, for all networks combined, the proportion of samples exceeding the USEPA Maximum Contaminant Level (MCL) of 10 mg/L as N for nitrate increased significantly. One network in the Delmarva Peninsula had a significant increase in the proportion of samples exceeding the MCL for nitrate.

A subset of 261 wells was sampled every other year (biennially) to evaluate decadal-scale changes using a time-series analysis. The analysis of the biennial data set showed that changes were generally similar to the findings from the analysis of decadal-scale change that was based on a step-trend analysis. Because of the small number of wells in a network with biennial data (typically 4–5 wells), the time-series analysis is more useful for understanding water-quality responses to changes in site-specific conditions rather than as an indicator of the change for the entire network.

Introduction

The goals of the U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Program are to assess the status and trends of water quality in the United States and to understand the factors that affect it (Gilliom and others, 2001). Thus, the assessment of trends in groundwater quality is a key component of the program. The design of the component for groundwater trends assessment is discussed in Rosen and Lapham (2008). The approach to assessing trends in groundwater quality includes the simulation and forecast of trends, an understanding of factors affecting trends, and a statistical analysis of water-quality data. Statistical analysis of groundwater data collected through 2004 was conducted for nitrate (Rupert, 2008) and pesticides (Bexfield, 2008). Analysis of the short-term variation in water quality (within-year variability) for NAWQA trends data was conducted by Rosen and others (2008). Additional regional trend studies of data from the program were conducted by Frans (2008), Burow and others (2008), Debrewer and others (2008), Paschke and others (2008), Saad (2008), and Dalton and Frick (2008).

Changes in concentrations of chloride, dissolved solids, and nitrate were evaluated as general indicators of water quality and the potability of drinking water. The U.S. Environmental Protection Agency (USEPA) has established National Secondary Drinking Water Regulations, referred to as Secondary Maximum Contaminant Levels (SMCLs), of 250 milligrams per liter (mg/L) and 500 mg/L for chloride and dissolved solids, respectively (U.S. Environmental Protection Agency, 2009). Because they are not regulatory, the SMCLs are referred to as guidelines. Chloride concentrations greater than 250 mg/L (the SMCL for chloride) are of concern because of a salty taste. In addition, groundwater is often a substantial component of stream base-flow discharge, so groundwater may be contributing chloride to streams. The chronic and acute criteria for chloride concentrations in streams as a potential concern for the health of aquatic life are 230 mg/L and 860 mg/L, respectively (U.S. Environmental Protection Agency, 1988). Changes in the concentrations of chloride or dissolved solids could also provide insight into possible sources of other contaminants. For example, chloride could be attributed to deicing sources or effluent from domestic septic systems. Dissolved solids in drinking water are a concern relevant to hardness, deposits, colored water, staining, and salty taste. Data from the 1960s through 1980s showed that levels of dissolved solids exceeded the SMCL of 500 mg/L in about half of the area of the basin-fill aquifers in the southwestern United States (Anning and others, 2010). The analysis of changes in dissolved solids may be used to evaluate the effects of salinity-control projects, such as those implemented in the southwestern United States (Colorado River Basin Salinity Control Forum, 2008).

NAWQA data collected during 1991–2007 indicate that nitrate is the most frequent anthropogenic contaminant to exceed human-health standards in water from domestic wells (1991–2004 data; DeSimone and others, 2009) and the second most frequent anthropogenic contaminant to exceed human-health standards in water from public-supply wells (1993–2007 data; Toccalino and others, 2010). As used in this report the term “nitrate” refers to concentrations measured as nitrite plus nitrate in mg/L as nitrogen (N). When nitrite concentrations were found to be negligible, the laboratory results for nitrite plus nitrate were considered to be equivalent to nitrate. Concentrations of nitrate in excess of the USEPA MCL of 10 mg/L as N in drinking water are associated with human-health problems (U.S. Environmental Protection Agency, 2009). The MCL is enforceable for public water supplies and thus is referred to as a standard. In addition, a large effort has been made at Federal, state, and local levels to control excess use of nutrients (U.S. Environmental Protection Agency, 2008); therefore, it is important to know whether those efforts have resulted in improvements in water quality.

This report is not intended to explore the causative factors leading to decadal-scale changes in chloride, dissolved solids, and nitrate concentrations. The intent is to compile available chloride, dissolved solids, and nitrate data collected by USGS through the NAWQA program to date (2010) and to statistically analyze these data at the national and well-network scale. The results of this analysis are not intended to be predictive. That is, the results do not imply that the direction and magnitude of observed changes will continue into the future. The paired samples from the decadal data set are evaluated to determine the magnitude, direction, and statistical significance of changes in concentration. Although these data are from networks designed for trend analysis and understanding trends is a goal of the NAWQA program, results of the evaluation of the limited decadal data (only two data points available per well) are referred to as a “change” rather than a “trend.” The time-series analysis of the biennial samples is based on multiple samples per well and is temporal in nature; thus, it is referred to as a trend analysis.

Purpose and Scope

The purpose of this report is to present results of analyses of decadal-scale changes in chloride, dissolved solids, and nitrate concentrations in groundwater measured from 1988 to 2010. Decadal-scale changes are evaluated by use of a step-trend analysis, comparing concentrations in paired samples from each of 1,235 wells in 56 networks. Statistical methods that account for large proportions of censored data (data reported as below some threshold) were selected to analyze the data. These 56 networks represent 22 principal aquifers that account for nearly 80 percent of the estimated withdrawals of groundwater used for drinking-water supply in the Nation (Maupin and Barber, 2005). Concentration changes are further evaluated using data from a subset of the 1,235 wells, consisting of 261 wells in 52 networks that were sampled biennially (every other year for 6–8 samples per well) to determine whether changes found using the step-trend analysis were also evident when using a time-series approach on a smaller data set. This report illustrates statistical and graphical methods that are the most appropriate for use in the analysis of the unique types of groundwater-quality data that are produced by the NAWQA program. The analysis for decadal-scale changes in nitrate concentrations supersedes the analysis of Rupert (2008) because there are minor differences in statistical approaches and additional data through 2010 (32 additional networks) were included.

Description of Networks

The primary analysis of groundwater-quality status and trends by NAWQA takes place at the network level (Gilliom and others, 2001). A groundwater network is a set of 20 to 30 wells selected using a stratified random approach in order to represent water-quality conditions in a given geographical area and aquifer (Lapham and others, 1995). In order to understand the results of the network sampling, it is important to be aware of the study design and the characteristics of the networks that were sampled.

The groundwater-sampling design includes two major types of well networks—land-use studies and major aquifer studies (Rosen and Lapham, 2008). A land-use study network is made up of about 20 to 30 shallow wells associated with a specific hydrogeology and land-use type; it is designed to indicate the effect of the targeted land use on the quality of recently recharged groundwater. Land-use studies were conducted in both urban and agricultural settings and were typically made up of monitoring or domestic wells. A major aquifer study network typically is made up of 20 to 30 domestic and public-supply wells that are located across the study area in order to characterize the quality of groundwater used primarily as a source of drinking water without regard to land use (Rosen and Lapham, 2008).

Since 1988, the NAWQA program has sampled more than 5,000 wells in nearly 200 networks (Dubrovsky and others, 2010). A subset of these well networks is designated for resampling on a periodic basis, and these networks are referred to as trend networks. The program operates in decadal cycles: Pilot Studies were conducted from 1988 to 1991, Cycle 1 studies were conducted from 1992 to 2000, Cycle 2 studies (ongoing as of the publication of this report) are scheduled to be conducted from 2001 through 2012. Trend networks had the first full-network sampling event during either the Pilot Study period or Cycle 1 and a second full-network sampling event during Cycle 2 (fig. 1). Data for this report were collected through 2010. Thus the decadal data set consists of comparisons of the first full-network sampling events conducted from 1988 to 2000 to the second full-network sampling events conducted from 2001 to 2010. Networks that have had two full-network sampling events on approximately a decadal time span include 1,235 wells in 56 land-use study or major aquifer study networks (fig. 1). Most of the wells in these networks have been sampled twice for nitrate, chloride, and dissolved solids (table 1, at end of report). The span between full-network resampling events ranged from 7 to 14 years; however, this is referred to hereafter as decadal-scale sampling (fig. 1). The networks include wells in 25 agricultural land-use studies, 13 urban land-use studies, and 18 major aquifer studies. Each trend network designated for resampling on the decadal scale also has a subset of about five wells that were sampled biennially (fig. 1). Only those networks with at least two rounds of full-network sampling were included in the time-series analysis of the biennial data for this report.

The naming convention for the networks includes a series of letters and numbers that provide key information about the network. The first four letters are the study-unit code, indicating the region of the country or major river basin where the sampling took place (fig. 2; table 1). These letters are followed by either “lus” for land-use study or “sus” for major aquifer study (from the previous name of the subunit survey). Urban land-use study networks then have a suffix of rc (residential-commercial) or rs (residential). Agricultural land-use studies have a suffix of cr (cropland), or (orchard), or ag (general agriculture). Networks also have a numeric or alphanumeric code to differentiate among similar network types. For example, gaflluscr1 is in the GAFL (Georgia-Florida Coastal Plain Study unit), is a land-use study (lus), is targeted on cropland (cr), and is the first in the series of studies in the GAFL done in that setting (1). These names are used in a number of figures and tables; therefore, it is important to understand their meaning when cross referencing a figure or table. Some network names include four letter study-unit codes that refer to a former study unit name. For example, networks with the prefix “dlmv” or “poto” are currently part of the combined PODL study unit (Potomac River Basin and Delmarva Peninsula), but the networks maintain their original names for continuity.

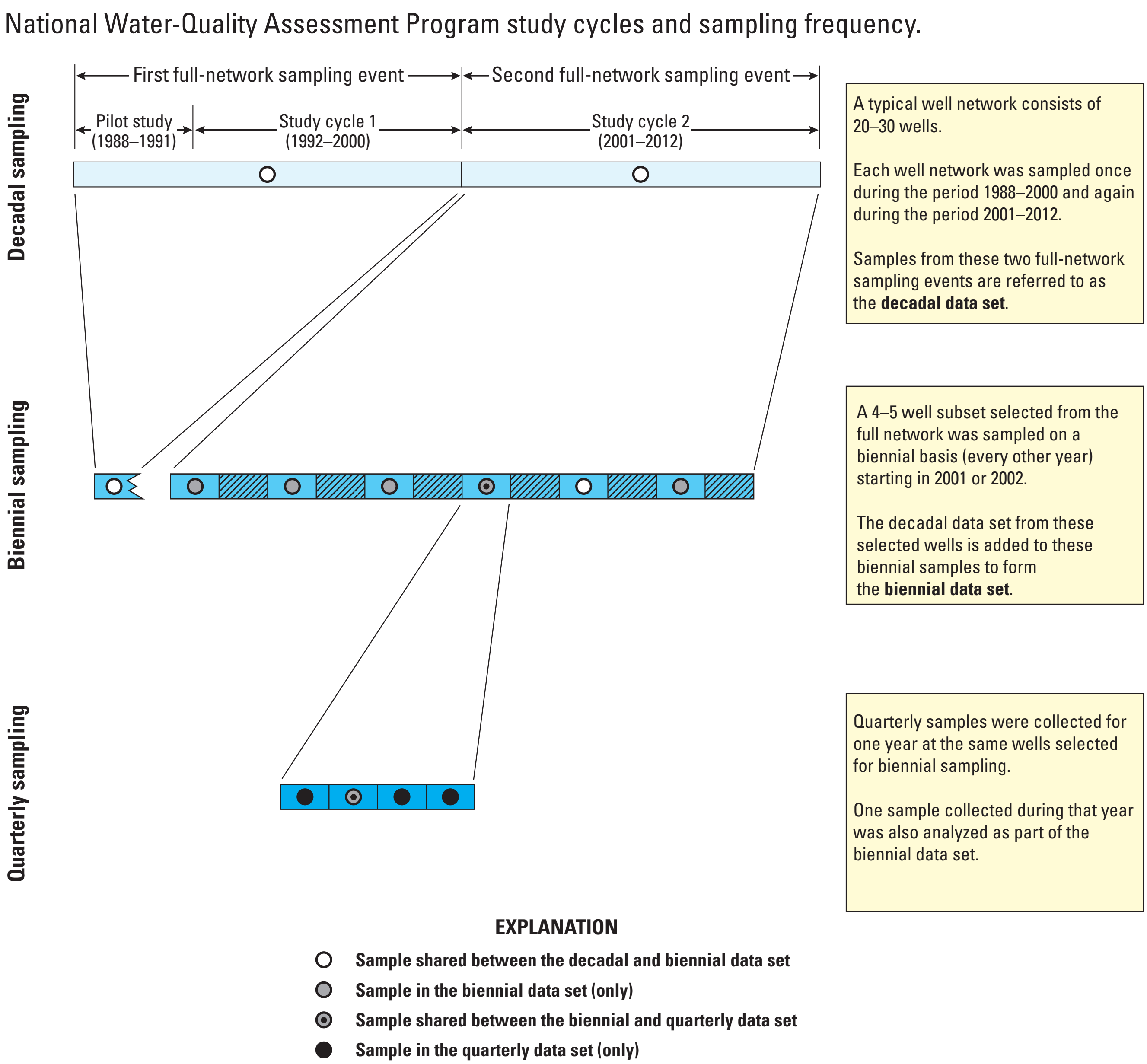
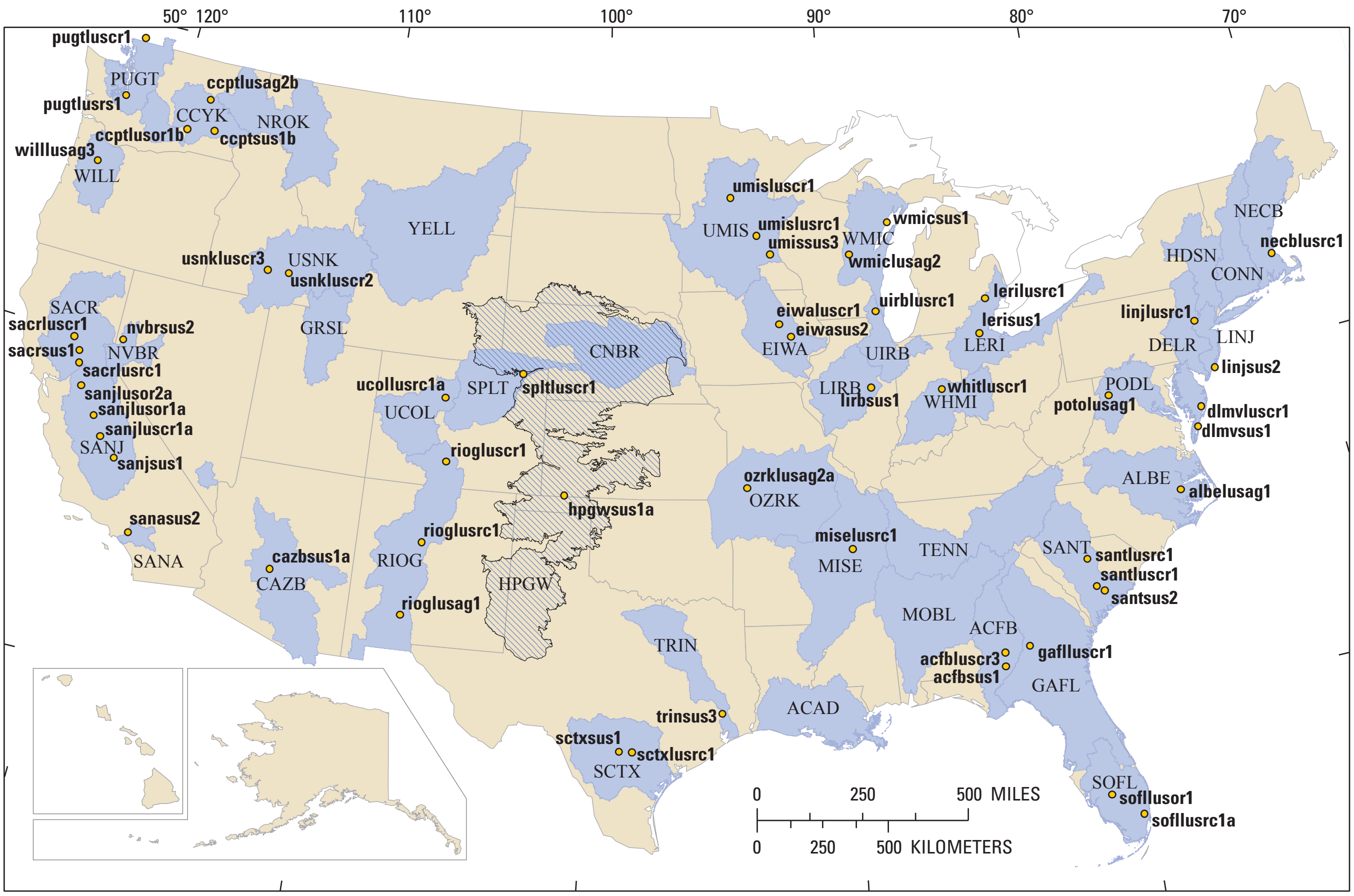


Figure 1. Example of a sampling scenario for one well network showing relations among cycles of the National Water-Quality Assessment Program, full network sampling events, biennial sampling, and quarterly sampling.



EXPLANATION

ACAD — **NAWQA Cycle 2 study unit area and identifier**

HPGW — **High Plains Regional Groundwater study area**

soflusrc1a — **Groundwater trends network centroid and abbreviation (See table 1 for network description.)**

Study unit name and abbreviation

ACAD	Acadian-Pontchartrain Drainages	OZRK	Ozark Plateaus
ACFB	Apalachicola-Chattahoochee-Flint River Basin	PODL	Potomac River Basin and Delmarva Peninsula
ALBE	Albemarle-Pamlico Drainage Basin	PUGT	Puget Sound Basin
CAZB	Central Arizona Basins	RIOG	Rio Grande Valley
CCYK	Central Columbia Plateau - Yakima River Basin	SACR	Sacramento River Basin
CNBR	Central Nebraska Basins	SANA	Santa Ana Basin
CONN	Connecticut, Housatonic and Thames River Basins	SANJ	San Joaquin-Tulare Basins
DELR	Delaware River Basin	SANT	Santee River Basin and Coastal Drainages
EIWA	Eastern Iowa Basins	SCTX	South-Central Texas
GAFL	Georgia-Florida Coastal Plain	SOFL	Southern Florida
GRSL	Great Salt Lake Basins	SPLT	South Platte River Basin
HDSN	Hudson River Basin	TENN	Tennessee River Basin
HPGW	High Plains Regional Ground Water Study	TRIN	Trinity River Basin
LERI	Lake Erie - Lake Saint Clair Drainages	UCOL	Upper Colorado River Basin
LINJ	Long Island - New Jersey Coastal Drainages	UIRB	Upper Illinois River Basin
LIRB	Lower Illinois River Basin	UMIS	Upper Mississippi River Basin
MISE	Mississippi Embayment	USNK	Upper Snake River Basin
MOBL	Mobile River Basin	WHMI	White, Great and Little Miami River Basins
NECB	New England Coastal Basins	WILL	Willamette Basin
NROK	Northern Rockies Intermontane Basins	WMIC	Western Lake Michigan Drainages
NVBR	Las Vegas Valley Area and the Carson and Truckee River Basins	YELL	Yellowstone River Basin

Figure 2. Locations of U.S. Geological Survey National Water-Quality Assessment Program study units and groundwater trends networks.

Well characteristics differ among study types and among aquifers. Wells in land-use studies generally have shallower depths (median depth 35 ft) than wells in major aquifer studies (median depth 160 ft; table 1); however, well depths also vary among aquifers. For example, median well depths in land-use studies in the San Joaquin-Tulare Basin study unit overlying the Central Valley aquifer system in California are greater than median well depths in major aquifer studies in many other aquifers across the Nation. Contaminant concentrations in deeper wells may be lower than those projected on the basis of current land-surface conditions when compared to contaminant concentrations in shallower wells. Potential reasons for lower contaminant concentrations in deeper wells include natural attenuation during the longer travel time needed for water to move to the well screen and the possibility that current conditions at the land surface may differ substantially from conditions at the land surface at the time of recharge. Because wells in major aquifer studies are typically deeper than wells in land-use studies, the water from those wells may be older and affected by a mixture of land-use types. Accordingly, from a temporal change perspective, water quality in the land-use study networks generally would be expected to respond more quickly to changes in land-use practices than water quality in the major aquifer study networks. However, compared to water from wells in the major aquifer study networks, water from wells in the land-use study networks may experience greater short-term variability in contaminant concentrations because of natural and hydrologic influences, which may make long-term changes difficult to detect with limited data such as the decadal-scale sampling. Other characteristics, such as aquifer hydraulic conductivity, geochemical processes, and variation in recharge rate, also affect water-quality responses to changes in contaminant sources.

Methods

The techniques for selecting the data on chloride, dissolved solids, and nitrate included in this analysis, and the statistical methods used to analyze the data, are described in the following sections. Two data sets were developed for the analyses: a decadal data set used for the step-trend analysis and a biennial data set used for time-series analysis (fig. 1).

Well and Network Selection

The NAWQA groundwater-quality sampling design incorporates full-network sampling on a decadal scale and biennial sampling for a subset of those wells (Rosen and Lapham, 2008). For the decadal data set analyzed in this report, sample results were compiled for calendar years 1988 through 2010. In most cases, to minimize potential seasonal differences, the month of sample collection during the first full-network sampling event was plus or minus 3 months of the sample collection month during the second full-network sampling event. In several networks, not all wells could be resampled because some were destroyed or the ownership changed. Networks with fewer than 10 wells sampled on a decadal-scale basis were not included in this analysis to improve validity of statistical comparisons between networks. As of 2010, 56 networks were available for decadal analysis.

For the biennial data set, a separate set of criteria were developed to determine which samples would be included in the time-series analysis. This was necessary in order to meet the requirements of the statistical tests and so that results would be comparable among networks. The statistical method requires a relatively evenly spaced temporal sampling interval. Because all samples were not collected on an even interval, the sampling intervals were evaluated for every well. Most of these wells were sampled on a quarterly basis for 1 year. For samples from that year, three of the four quarterly samples were excluded from the statistical analysis so that the sampling density remained at approximately one sample per year. The sample that was retained was the sample that matched the time of year when most of the biennial samples were collected at that well (fig. 1). Other samples at intervals of less than a year were excluded from the statistical analysis using the same approach. If a sample was on a near-annual basis, the sample was kept in the biennial data set.

The Regional Kendall statistical test was used for the time-series analysis of the biennial data set. Helsel and Hirsch (2002) recommend that the product of the number of wells and the number of samples per well is at least 25. Thus, with five wells in a typical network, five samples per well were considered a minimum goal for inclusion in the time-series analysis. Individual wells with fewer than four samples were excluded, and any network with fewer than four wells was excluded from the analysis. Therefore, the goal for the minimum number of samples for a network to be included in the biennial data set was 25 total samples. Also, only networks that were part of the decadal data set were included in the biennial data set. Fifty-two networks met these criteria and were available for time-series analysis.

Laboratory Reporting Levels

In order to conduct valid statistical analyses of the data, it was necessary to account for the long-term changes in laboratory reporting levels (LRLs) from 1988 through 2010. Because the statistical methods do not account for multiple LRLs, it was necessary to select a common assessment level before analyzing the data. Common assessment levels are used to provide a valid comparison among non-detections at a variety of LRLs. Setting a common assessment level for chloride and dissolved solids was straightforward. Almost all chloride analyses had a LRL of 0.1 mg/L. Only one chloride sample had a higher reporting level of 0.29 mg/L. The sample with the nondetect at a reporting level of 0.29 mg/L was excluded from the national (all networks combined) analysis but included in the network-level analysis as it was the only nondetect in that network. The highest LRL for dissolved solids was 10 mg/L.

No dissolved solids samples had reporting levels greater than 10 mg/L, so no further adjustments to the dissolved solids data were necessary.

From 1988 to 2010, the LRL for nitrate ranged from 0.04 to 0.1 mg/L as N. It is common practice to use the highest LRL (0.1 mg/L as N) as the common assessment level for statistical analysis. In this particular data set, however, using a common assessment level of 0.1 mg/L as N would have caused a large amount of the data to be analyzed as nondetects (less than 0.1 mg/L as N) instead of their reported values. Therefore, a common assessment level was selected that maximized the amount of information that could be interpreted from the available data. Nearly 98 percent of the results reported as nondetects had LRLs for nitrate of 0.04, 0.05, or 0.06 mg/L as N; so a common assessment level of 0.06 mg/L as N was used. This means that for statistical purposes, nondetects at 0.04, 0.05, and 0.06 mg/L as N and nitrate detections with values less than 0.06 mg/L as N were all evaluated as less than 0.06 mg/L as N. Samples from 13 wells in the dlmvluscr1 and dlmvsus1networks (table 1) analyzed during 1988 had LRLs of 0.1 mg/L as N. Those samples were excluded from the national-level statistical analysis because the LRL was larger than the common assessment level of 0.06 mg/L as N, and it was determined that more information would be retained by eliminating those 13 samples than by analyzing the entire data set using a common assessment level of 0.1 mg/L as N. Those 13 samples, however, were included in the network-level analysis of the dlmvluscr1 and dlmvsus1 well networks (where the network-specific common assessment level was set at 0.1 mg/L as N for nitrate) in order to maintain as much statistical information as possible.

Statistical Methods

Decadal-Scale Changes in Water Quality based on Step-Trend Analysis of the Decadal Data Set

The primary application of the statistical comparisons was to determine whether concentrations of chloride, dissolved solids, and nitrate have changed in well networks between the first full-network sampling event (1988–2000) and the second full-network sampling event (2001–2010). The analysis of change over a single time step is referred to as a two sample step-trend test (Helsel and Hirsch, 2002). When the same well has been sampled twice, step-trend tests, a type of matched-pair test, are typically used to determine statistically significant differences. Step-trend tests first calculate differences in concentrations at each well, and then the patterns of those changes are summarized at the group level (well network) to determine whether or not the observed pattern represents a statistically significant change in the network as a whole. The networks were designed with the number and distribution of wells to be representative of conditions in a specific part of an aquifer or land-use setting, thus the step-trend analysis of the networks is considered to be the best representation of changes in concentrations at the network level. Although there are numerous sources of variability that can affect changes in concentration measured in any pair of samples, a recent study indicates that actual long-term changes in concentration become the dominant source of variability for timescales greater than 3 years (McHugh and others, 2011). Thus, samples collected on a decadal time scale are likely to reflect an actual long-term change in concentration in the aquifer rather than a short-term change in concentration resulting from some other source of variability.

The conventional sign test and the Wilcoxon signed-rank test are nonparametric tests commonly used to evaluate statistical changes in paired data sets (Helsel and Hirsch, 2002); however, both of these tests ignore all tied data pairs. Tied data pairs can result from an actual tie in reported values from both sampling events, but more frequently tied pairs occur when data from both sampling events are nondetects. For statistical analysis, pairs of nondetects are effectively “tied” data because they are both evaluated at a common assessment level, such as less than 0.06 mg/L as N in the case of nitrate. In the NAWQA groundwater data set, ties can be quite common, so statistical tests that ignore tied data may result in a finding that there was a significant change in concentrations when in fact there was not. However, versions of both of these tests that have been modified to account for ties are available and are described below.

A modification of the sign test that accounts for tied values in the nonparametric ranking procedure (Fong and others, 2003; hereafter referred to as the modified sign test) was used in this study to evaluate changes for sample pairs in the decadal data set when ties were present. The sign test counts how many pairs increased and how many pairs decreased, and calculates a p-value, which quantifies the statistical level of significance of the increase or decrease. The modified sign test by Fong and others (2003) incorporates the tied values, which typically cause the p-values to be larger (less significant). It is important to determine whether tied pairs are present in a data set prior to selecting the conventional or modified sign test. The results of the modified sign test generally approach the results of the conventional sign test as the number of pairs of samples with ties approaches zero. However, if the modified sign test is used when tied pairs are not present and the data set has an even number of samples, results differ from the conventional sign test (Fong and others, 2003). Although Fong and others (2003) indicate that the difference is slight, large differences in p-values sometimes resulted when comparing results of the modified sign test to results of the conventional sign test during evaluation of data sets that had no pairs of ties. Thus the modified sign test was used only for data sets with tied pairs, and the conventional sign test was used in cases with no tied pairs. For this study, the procedure (macro) for calculating the modified sign test in R was used as described in Appendix J of Huston and Juarez-Colunga (2009).

The Wilcoxon signed-rank test (Wilcoxon, 1945) typically has more power to detect differences than the sign test because it accounts for the magnitude of change for each pair

(Helsel and Hirsch, 2002). A modification to the Wilcoxon signed-rank test was proposed by Pratt (1959) in which zero difference ties are included in the calculation (hereafter referred to as the Wilcoxon-Pratt signed-rank test). The Wilcoxon-Pratt signed-rank test calculates the difference between the first and second sampling event, ranks those differences (including the zero differences), discards the ranks from the zero differences (tied values), and then calculates a p-value based upon the remaining ranks. For this study, the "wilcoxsign_test (zero.method = c ("Pratt"))" command in the "coin" library of the R statistical package was used (Hothorn and others, 2008). The Wilcoxon-Pratt signed-rank test assumes that differences between values of sample pairs are symmetrically distributed. Although this assumption was not checked for the data from each network, it was estimated that the effect of any asymmetry on statistical results was small. Helsel and Hirsch (2002) indicate that the signed-rank test is relatively insensitive to violations of its assumptions and that asymmetry does not cause major problems with inaccurate p-values.

When computing the Wilcoxon-Pratt signed-rank test, the nitrate data had to be entered into the test data set in a manner so that the statistical test could distinguish between an actual detected value at 0.06 mg/L as N and a nondetect that had a reporting level of 0.06 mg/L as N. Nine wells had actual detections at 0.06 mg/L as N, but the common assessment level used for the nitrate data was also 0.06 mg/L as N. To assure that the Wilcoxon-Pratt signed-rank test correctly ranked the data, all nondetects at less than 0.06 mg/L as N (<0.06) were reassigned values of 0.0599. This ensured that the Wilcoxon-Pratt signed-rank test would differentiate between detect and nondetect values at 0.06, but the miniscule difference (0.0001) between 0.0599 and 0.06 does not affect the rankings of any of the other data because no other pairs of data had differences this small. An alternate method of substitution using zero for nondetects made only minor differences in p-values for a small number of networks but did not change the findings of significance. The alternate substitution method, therefore, is not reported nor discussed further. The conventional and modified sign tests also were run using a reassigned value of 0.0599 for nondetects. For these two tests, it makes no difference if the reassigned value is zero or 0.0599 because the conventional and modified sign tests do not take into account the magnitude of the differences between pairs.

It is important to note that a 90-percent confidence level (or p-value < 0.10) was used to identify well networks with significant differences in concentrations using the conventional sign, modified sign, and Wilcoxon-Pratt signed-rank tests. The 90-percent confidence interval was selected instead of a 95-percent confidence interval to provide a more conservative indication of changes in concentrations and to allow early warning in those cases that may not have been significant at the 95-percent confidence interval. In order to allow assessment of the confidence interval for each statistical test, tables of results show the actual probability values.

Fisher's exact test was used to analyze changes in the proportion of samples that exceeded a concentration threshold (Helsel and Hirsch, 2002). A two-by-two matrix is populated with the number of samples exceeding and not exceeding a regulatory standard or guideline in the first sampling event and the second sampling event. A Fisher's exact test is run to determine whether or not the proportion of wells exceeding the standard or guideline differs significantly between the two sampling events. Because this test can determine whether or not a significantly larger number of samples exceeded a regulatory standard or guideline (for example the primary or secondary maximum contaminant level) in one sampling event than in another sampling event, it provides insight on the relevance of the changes in concentrations beyond whether or not the concentrations changed. Because the exact test is used, the result is not affected when the distribution of the data is unbalanced. A 90-percent confidence level was used to indicate a statistically significant change in the proportion of samples exceeding a threshold.

The Turnbull estimator for median change, as described by Helsel (2005), was calculated as a measure of the magnitude of change in concentration between paired values. The Turnbull approach uses a survival method to calculate percentiles, such as the median, of differences in paired samples where there are censored data in one or more of the paired values; thus, these medians differ from medians that might be calculated using substitution methods, such as setting nondetects to their reporting level or setting nondetects to zero. A Minitab macro available at *http://practicalstats.com/index.html* implements the procedures to calculate the Turnbull median found in the textbook "Nondetects and Data Analysis" by Helsel (2005). Any references to median changes in concentration herein are to the Turnbull median of the difference in concentration between sampling events (sample 2 concentration – sample 1 concentration), and the magnitude of the Turnbull median is considered relevant only if the Wilcoxon-Pratt signed-rank test indicated a statistically significant change. Positive values indicate an increase in the median concentration difference from the first sampling event to the second sampling event.

Decadal-Scale Changes in Water Quality Based on Time-Series Analysis of the Biennial Data Set

The time-series analysis of the biennial data set is another way to evaluate decadal-scale trends at the individual well and network level. Data were collected over a period of up to 24 years, but the vast majority of the data were from the period of 1998 to 2010, so it is still referred to as a decadal-scale analysis. The Regional Kendall test (Helsel and others, 2006) was used to analyze changes in concentrations for groups of wells in designated networks. It is a nonparametric statistical test typically used to assess changes in water-quality data and is used to evaluate whether the slope of the change in concentration is significantly different than zero for a group of wells. The Regional Kendall test, a modification of the Seasonal Kendall test, performs the Mann-Kendall test for individual wells, then combines the results to determine whether or not there is a significant increase or decrease in the dependent variable over time (Helsel and others, 2006). If the test p-value was less than 0.1, changes were considered statistically significant at a 90-percent confidence level. The Regional Kendall test calculates the slope of the annual change in concentration; however, the slope is relevant only if the change was considered statistically significant. The number of wells per network in the biennial data set (4 to 6 wells) was much smaller than the number of wells in the decadal data set (10 to 30 wells). Although the results of the time-series analysis are reported at the network level, the biennial sampling wells represent a much smaller part of the aquifer targeted by that network than the wells used for the step-trend analysis (the full network resampling); therefore, the results of the biennial analysis are considered supplementary information that can enhance the understanding of trends, rather than a representation of conditions in the network as a whole.

Serial correlation, which is short-term correlation between observations, is a potential issue affecting the validity of Regional Kendall tests. Typically, this is a concern when sample spacing is frequent, such as monthly, but Hirsch and Slack (1984) indicate that typically 10 years of data are needed to detect serial correlation. The Durbin-Watson statistic (SAS Institute Inc., 2010) was used to evaluate the data for serial correlation and, in general, showed that serial correlation was not an important issue affecting the results.

Quality Assurance and Quality Control

Data were collected in a consistent manner in accordance with protocols set forth by the NAWQA program (Koterba and others, 1995; U.S. Geological Survey, variously dated). In studies where variability or trends are of interest, the potential effects of variability in laboratory analysis and sampling on trend analysis were analyzed. Potential issues related to laboratory analysis were evaluated by summarizing data from the laboratory internal quality-control program. In order to assess the reliability and consistency of the sampling, quality assurance and quality control were assessed by Mueller and Titus (2005) and Gross and others (2012). Three areas related to sampling that could potentially affect the evaluation of groundwater trends are contamination bias, as evaluated by the blank-water analysis; sampling variability in measurements, as evaluated by comparing pairs of replicates; and trends in variability, also evaluated by the comparing pairs of replicates.

Since 1981, the USGS has operated an independent quality-assurance project called the Inorganic Blind Sample Program (U.S. Geological Survey, 1997). The purpose of the Inorganic Blind Sample Program (IBSP) is to monitor and evaluate the quality of laboratory analytical results through the use of double-blind quality-control reference samples. The blind reference samples submitted by the IBSP to the NWQL indicate that there was no significant long-term bias in chloride, dissolved solids, or nitrate concentrations reported by the NWQL and that nitrate data reported by the NWQL are suitable for analysis of trends of nitrate in groundwater because there is little likelihood that analytical accuracy and precision will affect trends. From 1991 through 2009, 3,484 blind spike samples for chloride analysis were submitted by the IBSP to the NWQL. The median percent recovery was about 100 percent, and only 1.7 percent of the samples exceeded two standard deviations from the most probable value (spike concentration). From 1991 through 2009, 3,455 blind spike samples were submitted by the IBSP to the NWQL for analysis of dissolved solids. The median percent recovery was about 101 percent. Only 2.6 percent of the dissolved solids samples exceeded two standard deviations from the most probable value (spike concentration). From 1991 through 2009, 3,980 blind spike samples for nitrate were submitted by the IBSP to the NWQL. The median percent recovery of the nitrate spikes was about 98 percent. Only about 1.5 percent of the nitrate samples exceeded two standard deviations from the most probable value (spike concentration).

Gross and others (2012) evaluated contamination bias, sampling variability, and trends in sampling variability for chloride. Chloride contamination was determined with a 99-percent confidence level to be less than 0.3 mg/L in 95 percent of the samples, a level which makes it unlikely that contamination bias had an appreciable effect on the assessment of trends. The assessment of sampling variability also indicated a maximum standard deviation of 0.7 mg/L for chloride concentrations less than 100 mg/L and 1.5 percent for concentrations greater than or equal to 100 mg/L. The standard deviation of 0.7 mg/L was actually only for a single year, 1999. The standard deviation for most of the other years was much lower, but because the standard deviation changed from year to year, the maximum value was used for this assessment. This variability does not affect the statistical results for networks where statistically significant changes were found, but it can be used to estimate a boundary below which sample variability could potentially mask environmental changes. Environmental changes greater than 0.7 mg/L for samples of less than 100 mg/L are unlikely to have been masked by the sampling variability, and environmental changes greater than 3 mg/L are unlikely to have been masked in networks with concentrations of about 200 mg/L. The type of changes that could be masked because of sampling variability would be in the range that typically would be considered practically insignificant in most cases.

Gross and others (2012) also evaluated contamination bias, sampling and analytical variability, and variation in sampling variability over time for dissolved solids (referred to as TDS in that report). TDS contamination was determined to be less than 12 mg/L in 95 percent of the blank samples, and 99 percent of environmental samples had concentrations larger—generally much larger—than 12 mg/L. Thus the bias caused by this level of contamination is considered to be small and have a negligible effect on interpretation of the trend data. The sampling variability (standard deviation) for TDS was 7 mg/L for samples with concentrations less than 1,000 mg/L and 3.2 percent (relative standard deviation) for samples with concentrations greater than or equal to 1,000 mg/L. The potential effect on analysis of changes in environmental samples is that true environmental changes of greater than 7 mg/L are not likely to have been masked for samples with concentrations less than 1,000 mg/L and changes greater than 64 mg/L are not likely to have been masked for networks with concentrations of about 2,000 mg/L. The variability in TDS replicate samples was constant over time.

Mueller and Titus (2005) evaluated blank samples and determined, with a 99-percent confidence interval, that contamination by nitrate plus nitrite in groundwater was less than 0.3 mg/L as N in 99 percent of samples and, thus, had no significant effect on measured concentrations. Mueller and Titus also evaluated the potential effect of sampling variability and analytical variability in nitrate concentrations on pairs of samples and determined a standard deviation of 0.043 mg/L as N for samples with concentrations less than 1 mg/L as N and a relative standard deviation (RSD) of 2.9 percent for samples with concentrations greater than or equal to 1 mg/L as N. This sampling and analytical variability applies to comparisons of single pairs of samples, but the effect of this variability is moderated when evaluating groups of samples (Mueller and Titus, 2005). No method is available to assess the effects of sampling variability on the results of the specific statistical tests used; however, the standard deviations and RSDs can provide some insight when comparing the sampling variability to the magnitude of change. A finding of a statistically significant change is evidence that the environmental signal was not masked. The potential effect of sampling variability on trend assessment is that trends might be masked if the sampling variability was greater than the environmental variability, leading to a false negative finding. As an example, environmental concentration differences greater than 0.043 mg/L as N (the standard deviation for samples less than 1 mg/L as N) probably would not be masked for samples with concentrations less than 1 mg/L as N. Environmental concentration differences greater than 0.29 mg/L as N probably would not be masked if the concentration was about 10 mg/L as N. This is calculated by multiplying the RSD for samples with concentrations greater than 1 mg/L as N (2.9 percent) by the selected concentration (10 mg/L as N). In samples with concentrations of 10 mg/L as N, differences in concentrations that were smaller than 0.29 mg/L as N may or may not have been masked. The evaluation of temporal trends in the variability of nitrate indicated no statistically significant trend; thus, there was no significant effect on the analysis for this report.

Decadal-Scale Changes in Concentrations of Chloride, Dissolved Solids, and Nitrate

Decadal-scale changes are primarily evaluated using a step-trend analysis based on a full network sampling twice at an interval of about 10 years. Decadal-scale changes from the full network sampling are considered the best indicator of change because the wells are selected to represent conditions in the entire network. Decadal-scale changes in concentration also are evaluated by a time-series analysis of the results from a subset of four to five wells in each network that had samples collected on a more frequent basis, typically biennially. The results of the time-series analysis are not necessarily representative of the changes at the network scale, but they are useful in understanding temporal patterns and variability of concentrations.

Changes in Concentrations Based on Step-Trend Analysis of the Decadal Data Set

Decadal-scale changes in concentrations are evaluated for chloride, dissolved solids, and nitrate using statistical tests including either the sign test (ties absent) or modified sign test (ties present), the Wilcoxon-Pratt test, and the Fischer's exact test. If the changes are found to be statistically significant at the network level, the Turnbull median may be used as an indication of the magnitude of the change in concentration and is reported as the median difference in concentration between the second sample and first sample, where a positive value indicates an increase over time and a negative value indicates a decrease over time.

Chloride

Of the 56 networks that were analyzed for changes in chloride concentrations using the Wilcoxon-Pratt signed-rank test, 24 had statistically significant increases in concentrations (table 2). Of the 24, five networks had statistically significant changes and median concentration changes of greater than 20 mg/L: lerilusrc1 (Lake Erie–Lake Saint Clair Drainages), necblusrc1 (New England Coastal Basin), rioglusag1 (Rio Grande Valley), uirblusrc1 (Upper Illinois Basin), and umislusrc1 (Upper Mississippi Basin). The largest increases in median chloride concentrations were in the uirblusrc1 (Upper Illinois River Basin–residential commercial land use) network, which had an increase in median concentration of 67 mg/L, and the necblusrc1 network (New England Coastal Basins–residential commercial land use), which had an increase in median concentration of 34 mg/L. Eleven of the 24 networks with statistically significant increases in chloride concentrations had median changes of 1 to 20 mg/L, and 8 other networks had median changes of less than 1 mg/L. Two networks, sctxsus1 (South-Central Texas) and usnkluscr3 (Upper Snake River Basin), had statistically significant decreases in concentrations of chloride, with median concentration decreases of 0.66 mg/L and 1.0 mg/L, respectively.

The results of the sign test for individual networks indicate that 20 of the 56 networks had statistically significant changes in chloride and were in agreement with results of the Wilcoxon-Pratt signed-rank test (table 2). Of these 20 networks, 18 had increased concentrations, and 2 had decreased

Table 2. Decadal-scale changes in chloride concentrations in groundwater in the U.S. Geological Survey National Water-Quality Assessment Program well networks in the United States, 1988–2010, based on step-trend analysis of the decadal data set.

[NA, not applicable; shading indicates modified sign test was used instead of conventional sign test owing to tied pairs; **bold** indicates statistically significant result at greater than a 90-percent confidence level; **(+)**, indicates a statistically significant increase in concentration at greater than a 90-percent confidence level; **(–)**, indicates a statistically significant decrease in concentration at greater than a 90-percent confidence level; mg/L, milligrams per liter; <, less than]

Network name	Number of pairs of samples	Result of sign test, probability value	Results of Wilcoxon-Pratt signed-rank test, probability value	Statistically significant result	Turnbull median concentration change, in mg/L	Number of sites with concentration exceeding 250 mg/L: First full-network sampling event	Number of sites with concentration exceeding 250 mg/L: Second full-network sampling event	Probability value from Fischer's exact test
All networks combined	[1]1,226	**<.001**	**<.001**	(+)	**0.59**	29	39	0.27
acfbluscr3	19	1.00	0.841		0.01	0	0	NA
acfbsus1	21	**0.027**	**0.015**	(+)	**0.35**	0	0	NA
albelusag1	12	0.774	0.433		0.59	0	0	NA
cazbsus1a	24	0.541	0.304		1.4	10	11	1.00
ccptlusag2b	16	0.454	0.255		-2.1	0	0	NA
ccptlusor1b	19	1.00	0.778		0.64	0	0	NA
ccptsus1b	30	0.201	0.111		0.69	0	1	1.00
dlmvluscr1	16	0.210	**0.020**	(+)	**9.9**	0	1	1.00
dlmvsus1	23	**0.093**	**0.014**	(+)	**1.8**	0	0	NA
eiwaluscr1	30	0.201	0.185		0.58	0	0	NA
eiwasus2	30	**0.045**	**0.012**	(+)	**0.31**	0	0	NA
gaflluscr1	20	0.428	0.161		0.29	0	0	NA
hpgwsus1a	30	**0.018**	**0.005**	(+)	**1.5**	0	0	NA
lerilusrc1	29	**0.063**	**0.039**	(+)	**25**	4	4	1.00
lerisus1	27	**0.021**	**0.008**	(+)	**0.54**	1	1	1.00
linjlusrc1	27	0.124	**0.046**	(+)	**5.0**	0	1	1.00
linjsus2	25	0.230	**0.093**	(+)	**0.98**	0	0	NA
lirbsus1	28	0.850	0.633		-0.07	0	0	NA
miselusrc1	20	0.824	0.823		1.0	0	0	NA
necblusrc1	21	**0.027**	**0.012**	(+)	**34**	1	3	0.61
nvbrsus2	16	**0.077**	**0.034**	(+)	**1.8**	0	0	NA
ozrklusag2a	20	0.503	0.247		0.51	0	1	1.00
potolusag1	24	**0.023**	**0.028**	(+)	**2.2**	0	0	NA
pugtluscr1	18	0.815	0.648		0.95	0	0	NA
pugtlusrs1	24	0.839	0.475		0.39	0	0	NA
rioglusag1	25	**0.015**	**0.014**	(+)	**30**	2	2	1.00
riogluscr1	12	0.774	0.239		-0.19	0	0	NA
rioglusrc1	10	0.754	0.575		4.6	0	0	NA
sacrluscr1	21	0.189	0.192		-1.0	2	1	1.00
sacrlusrc1	18	1.00	0.557		-0.98	1	1	1.00

Table 2. Decadal-scale changes in chloride concentrations in groundwater in the U.S. Geological Survey National Water-Quality Assessment Program well networks in the United States, 1988–2010, based on step-trend analysis of the decadal data set.—Continued

[NA, not applicable; shading indicates modified sign test was used instead of conventional sign test owing to tied pairs; **bold** indicates statistically significant result at greater than a 90-percent confidence level; **(+)**, indicates a statistically significant increase in concentration at greater than a 90-percent confidence level; **(–)**, indicates a statistically significant decrease in concentration at greater than a 90-percent confidence level; mg/L, milligrams per liter; <, less than]

Network name	Number of pairs of samples	Result of sign test, probability value	Results of Wilcoxon-Pratt signed-rank test, probability value	Statistically significant result	Turnbull median concentration change, in mg/L	Number of sites with concentration exceeding 250 mg/L		Probability value from Fischer's exact test
						First full-network sampling event	Second full-network sampling event	
sacrsus1	28	0.571	0.274		0.69	1	1	1.00
sanasus2	14	**0.057**	**0.041**	(+)	**5.2**	0	0	NA
sanjluscr1a	18	1.00	0.983		1.5	0	0	NA
sanjlusor1a	17	0.332	0.356		-0.96	0	0	NA
sanjlusor2a	19	0.167	**0.040**	(+)	**1.8**	0	0	NA
sanjsus1	26	0.556	0.439		1.0	1	1	1.00
santluscr1	18	0.815	0.122		0.53	0	0	NA
santlusrc1	21	**0.078**	**0.085**	(+)	**0.40**	0	0	NA
santsus2	29	0.458	0.370		0.12	1	2	1.00
sctxlusrc1	30	**0.045**	**0.005**	(+)	**1.5**	0	0	NA
sctxsus1	23	**0.093**	**0.089**	(–)	**-0.66**	0	0	NA
sofllusor1	18	**0.096**	**0.028**	(+)	**19**	0	0	NA
sofllusrc1a	13	0.581	0.382		0.07	0	0	NA
spltluscr1	29	0.265	**0.053**	(+)	**12**	0	0	NA
trinsus3	17	0.629	0.407		-0.83	1	1	1.00
ucollusrc1	15	1.00	0.394		0.32	0	0	NA
uirblusrc1	18	**0.031**	**0.035**	(+)	**67**	3	5	0.69
umisluscr1	22	0.832	0.592		0.80	0	0	NA
umislusrc1	26	**0.003**	**0.006**	(+)	**24**	1	2	1.00
umissus3	22	0.134	**0.058**	(+)	**0.36**	0	0	NA
usnkluscr2	26	0.845	0.534		-1.1	0	0	NA
usnkluscr3	28	**<.001**	**<.001**	(–)	**-1.0**	0	0	NA
whitluscr1	20	1.00	0.502		0.96	0	0	NA
willlusag3	24	**0.064**	**0.021**	(+)	**0.46**	0	0	NA
wmiclusag2	26	0.845	0.949		0.20	0	0	NA
wmicsus1	25	**0.043**	**0.021**	(+)	**0.65**	0	0	NA

[1] Number of samples used for "all networks combined" calculations (1,226) is not equal to the sum of the number of samples for individual networks (1,227). For the "all networks combined" calculations, one sample from the uirblusrc1 network with an elevated reporting level was excluded as described in the Methods section.

concentrations. As described in the methods section, the sign test is less sensitive than the Wilcoxon-Pratt signed-rank test because the sign test compares the number of increased concentrations to the number of decreased concentrations without regard to magnitude of change of those concentrations. Therefore, it is not unexpected that the results of the two tests are slightly different and that fewer significant changes were found using the sign test.

Results of both the modified sign test and Wilcoxon-Pratt signed-rank test for the 1,226 wells from all networks combined indicate a statistically significant increase in overall chloride concentrations, with a Turnbull median value of change in concentration of chloride of 0.59 mg/L (table 2). When evaluated using the Fischer's exact test, no statistically significant shift in the proportion of wells exceeding the SMCL of 250 mg/L was observed from the first to second sampling event, whether evaluating all networks combined or within individual networks (table 2).

The geographic distribution of the patterns of change in chloride concentrations, based on the Wilcoxon-Pratt test results, is shown in figure 3. Ten of the networks with increased concentrations of chloride were in major aquifer studies, seven were in agricultural land-use studies, and seven were in urban land-use studies. Potential sources of chloride are numerous and include agricultural fertilizers, runoff from deicing chemicals or salt used for deicing, saltwater intrusion from oceans, and on-site wastewater disposal. Specific analysis of the causes of changes is not within the scope of this report, but it is worth noting that four of the five networks with the largest increases in median chloride concentrations are urban land-use networks in the Northeast and upper Midwest (fig. 3). The only two well networks with statistically significant decreases in chloride concentrations are in southern Idaho and southern Texas (fig. 3).

Dissolved Solids

Of 54 networks that were analyzed for changes in dissolved solids using the Wilcoxon-Pratt signed-rank test, 22 had statistically significant increases (table 3). Five networks had statistically significant changes and median changes in concentrations that were greater than 50 mg/L: sofllusor1 (Southern Florida), lerilusrc1 (Lake Erie-Lake Saint Clair Drainages), necblusrc1 (New England Coastal Basin), uirblusrc1 (Upper Illinois River Basin), and rioglusag1 (Rio Grande Valley; table 3). The median dissolved solids concentration in the uirblusrc1 network (Upper Illinois River Basin) increased 160 mg/L over the decadal period, and median dissolved solids increased 260 mg/L in the rioglusag1 network (Rio Grande Valley). Three of the networks with increases in concentrations of dissolved solids greater than 50 mg/L were in networks where the median concentration of the network exceeded the USEPA SMCL of 500 mg/L during the second full-network sampling event (fig. 4). One network, acfbluscr3 (Apalachicola-Chattahoochee-Flint River Basin), had a statistically significant decrease in the median concentration of dissolved solids, with a median decrease of 6.0 mg/L.

The results of the sign test indicated 14 networks had significant changes in dissolved solids concentrations (table 3). Of the networks determined to have significant changes using the sign test, all had increased concentrations, and 12 were among the networks also identified by the Wilcoxon-Pratt signed-rank test as having a statistically significant increase.

A statistically significant increase in dissolved solids concentrations (using the Wilcoxon-Pratt signed-rank test) was observed when evaluating all well networks combined, and the median dissolved solids concentrations increased by 8.9 mg/L (table 3). Results of the sign test for all networks combined also indicated a statistically significant increase in dissolved solids concentrations. Results of Fisher's exact test of dissolved solids data from all networks combined indicated that there was a statistically significant increase in the proportion of samples with concentrations exceeding the SMCL of 500 mg/L (table 3).

The geographic distribution of the patterns of change in dissolved solids concentrations, based on the Wilcoxon-Pratt test results, can be seen in figure 4. Eight of the networks with increased concentrations of dissolved solids were in major aquifer studies, eight were in agricultural land-use studies, and six were in urban land-use studies. Areas with the largest magnitude of change in dissolved solids concentrations are in urban areas of the Northeast and upper Midwest and in agricultural areas in the Southwest and Florida (fig. 4).

Nitrate

Of the 56 networks analyzed for changes in nitrate concentrations using the Wilcoxon-Pratt signed-rank test, 18 had statistically significant changes. Thirteen networks had statistically significant increases, and five had statistically significant decreases. Three of the 13 networks with statistically significant changes—sanjluscr1a (San Joaquin-Tulare Basins), spltluscr1 (South Platte River Basin), and wmiclusag2 (Western Lake Michigan Drainages)—had statistically significant changes and median increases of greater than 0.5 mg/L as N of nitrate (table 4). All of the networks with median increases in concentrations of nitrate greater than 0.5 mg/L as N were in agricultural land-use studies. Two of the networks with median increases in concentrations of nitrate greater than 0.5 mg/L as N were in networks where the median nitrate concentration of the network exceeded the USEPA MCL of 10 mg/L as N during the second full-network sampling event (fig. 5). Of the five networks with statistically significant decreases in nitrate concentrations, all but one had median changes of less than 0.1 mg/L as N. The santluscr1 (Santee River and Coastal Drainages) network had a statistically significant decrease in nitrate concentrations with a median decrease of 0.63 mg/L as N. The sign test results indicate that five networks had

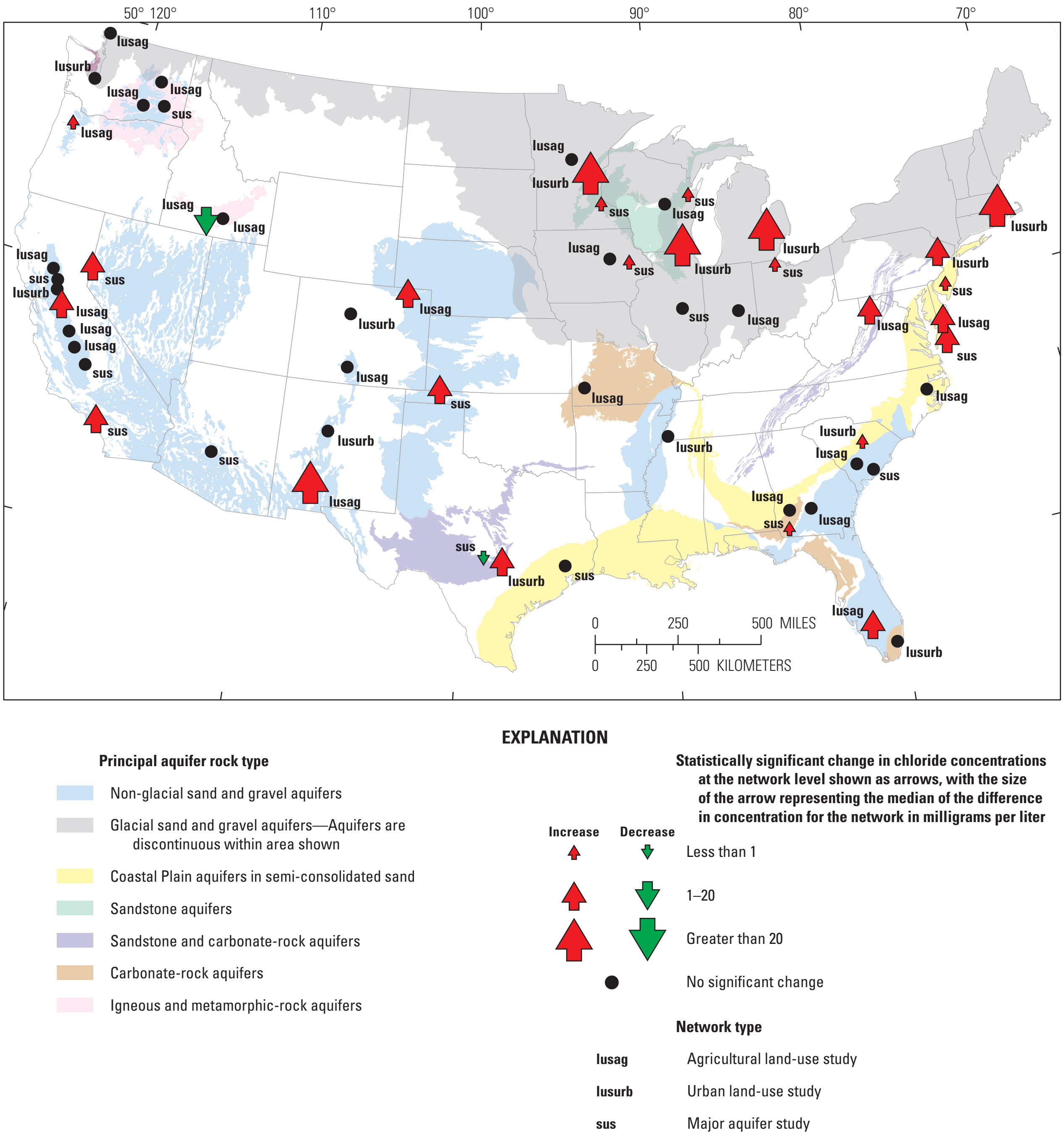


Figure 3. Locations of U.S. Geological Survey National Water-Quality Assessment Program well networks with and without statistically significant decadal-scale changes of chloride concentrations in groundwater in the United States 1988–2010, based on step-trend analysis of decadal data set using the Wilcoxon-Pratt signed rank test.

Table 3. Decadal-scale changes in dissolved solids concentrations in groundwater in the U.S. Geological Survey National Water-Quality Assessment Program well networks in the United States, 1988–2010, based on step-trend analysis of the decadal data set.

[NA, not applicable; **bold**, indicates statistically significant result at greater than a 90-percent confidence level; **(+)**, indicates a statistically significant increase in concentration at greater than a 90-percent confidence level; **(–)**, indicates a statistically significant decrease in concentration at greater than a 90-percent confidence level; mg/L, milligrams per liter; <, less than]

Network name	Number of pairs of samples	Result of sign test, probability value	Results of Wilcoxon-Pratt signed-rank test, probability value	Statistically significant result	Turnbull median concentration change, in mg/L	Number of sites with concentrations exceeding 500 mg/L		Probability value from Fischer's exact test
						First full-network sampling event	Second full-network sampling event	
All networks combined	1,184	**<0.001**	**<0.001**	(+)	**8.9**	246	291	**0.031**
acfbluscr3	19	0.359	**0.077**	(–)	**-6.0**	0	0	NA
acfbsus1	21	0.189	0.244		4.1	0	0	NA
albelusag1	12	0.146	0.158		3.0	0	0	NA
cazbsus1a	24	0.152	**0.022**	(+)	**32**	13	13	1.00
ccptlusag2b	16	0.804	0.642		-4.9	7	9	0.724
ccptlusor1b	19	0.359	0.334		-3.0	12	11	1.00
ccptsus1b	30	**0.002**	**<0.001**	(+)	**14**	2	3	1.00
dlmvluscr1	NA	NA	NA	NA	NA	NA	NA	NA
dlmvsus1	NA	NA	NA	NA	NA	NA	NA	NA
eiwaluscr1	30	0.584	0.704		-16	2	2	1.00
eiwasus2	30	0.361	**0.072**	(+)	**6.3**	4	6	0.731
gaflluscr1	20	0.824	0.455		4.9	0	0	NA
hpgwsus1a	29	1.00	0.239		0.24	3	6	0.470
lerilusrc1	29	**0.001**	**0.028**	(+)	**72**	11	18	0.114
lerisus1	27	0.700	0.885		2.4	4	4	1.00
linjlusrc1	27	**0.002**	**0.003**	(+)	**18**	0	1	1.00
linjsus2	25	1.00	0.904		-0.56	0	0	NA
lirbsus1	28	0.186	**0.062**	(+)	**7.4**	11	13	0.788
miselusrc1	20	**0.012**	0.167		7.4	1	1	1.00
necblusrc1	20	0.115	**0.040**	(+)	**61**	2	2	1.00
nvbrsus2	16	0.804	0.796		11	1	1	1.00
ozrklusag2a	20	**0.003**	**0.005**	(+)	**24**	1	1	1.00
potolusag1	24	**0.064**	**0.013**	(+)	**27**	2	5	0.416
pugtluscr1	18	**0.031**	**0.071**	(+)	**34**	0	0	NA
pugtlusrs1	23	0.405	0.136		15	0	0	NA
rioglusag1	25	0.108	**0.032**	(+)	**260**	23	24	1.00
riogluscr1	12	0.774	0.480		-8.5	3	3	1.00
rioglusrc1	10	0.754	0.879		-30	5	6	1.00
sacrluscr1	21	0.664	0.217		-20	13	12	1.00

Table 3. Decadal-scale changes in dissolved solids concentrations in groundwater in the U.S. Geological Survey National Water-Quality Assessment Program well networks in the United States, 1988–2010, based on step-trend analysis of the decadal data set.—Continued

[NA, not applicable; **bold**, indicates statistically significant result at greater than a 90-percent confidence level; **(+)**, indicates a statistically significant increase in concentration at greater than a 90-percent confidence level; **(–)**, indicates a statistically significant decrease in concentration at greater than a 90-percent confidence level; mg/L, milligrams per liter; <, less than]

Network name	Number of pairs of samples	Result of sign test, probability value	Results of Wilcoxon-Pratt signed-rank test, probability value	Statistically significant result	Turnbull median concentration change, in mg/L	Number of sites with concentrations exceeding 500 mg/L		Probability value from Fischer's exact test
						First full-network sampling event	Second full-network sampling event	
sacrlusrc1	18	0.481	0.711		17	8	9	1.00
sacrsus1	28	**0.014**	**0.014**	(+)	**18**	3	4	1.00
sanasus2	14	**0.057**	**0.074**	(+)	**10**	5	6	1.00
sanjluscr1a	18	**0.001**	**0.007**	(+)	**26**	9	10	1.00
sanjlusor1a	17	0.629	0.705		5.0	2	6	0.225
sanjlusor2a	19	0.359	**0.044**	(+)	**15**	2	2	1.00
sanjsus1	26	0.327	0.159		12	6	7	1.00
santluscr1	18	0.815	0.845		-3.3	0	0	NA
santlusrc1	21	0.383	**0.079**	(+)	**3.4**	0	0	NA
santsus2	29	0.458	0.275		-3.3	3	3	1.00
sctxlusrc1	30	0.201	**0.019**	(+)	**16**	0	0	NA
sctxsus1	22	0.286	0.115		6.7	1	1	1.00
sofllusor1	18	**0.096**	**0.071**	(+)	**64**	2	7	0.121
sofllusrc1a	13	1.00	0.807		-1.5	1	2	1.00
spltluscr1	29	0.265	0.347		43	29	29	NA
trinsus3	17	1.00	0.906		0.82	4	4	1.00
ucollusrc1	15	1.00	0.910		-7.9	1	2	1.00
uirblusrc1	18	**0.096**	**0.028**	(+)	**160**	15	15	1.00
umisluscr1	22	0.286	**0.067**	(+)	**30**	3	3	1.00
umislusrc1	26	0.556	0.144		44	14	19	0.249
umissus3	22	0.134	**0.077**	(+)	**12**	0	0	NA
usnkluscr2	26	0.556	0.694		3.1	8	7	1.00
usnkluscr3	28	0.571	0.246		-1.9	0	0	NA
whitluscr1	20	0.824	0.654		1.5	4	5	1.00
willlusag3	24	**0.064**	0.110		7.0	1	1	1.00
wmiclusag2	26	0.556	0.292		8.5	2	3	1.00
wmicsus1	25	**<0.001**	**<0.001**	(+)	**18**	3	5	0.702

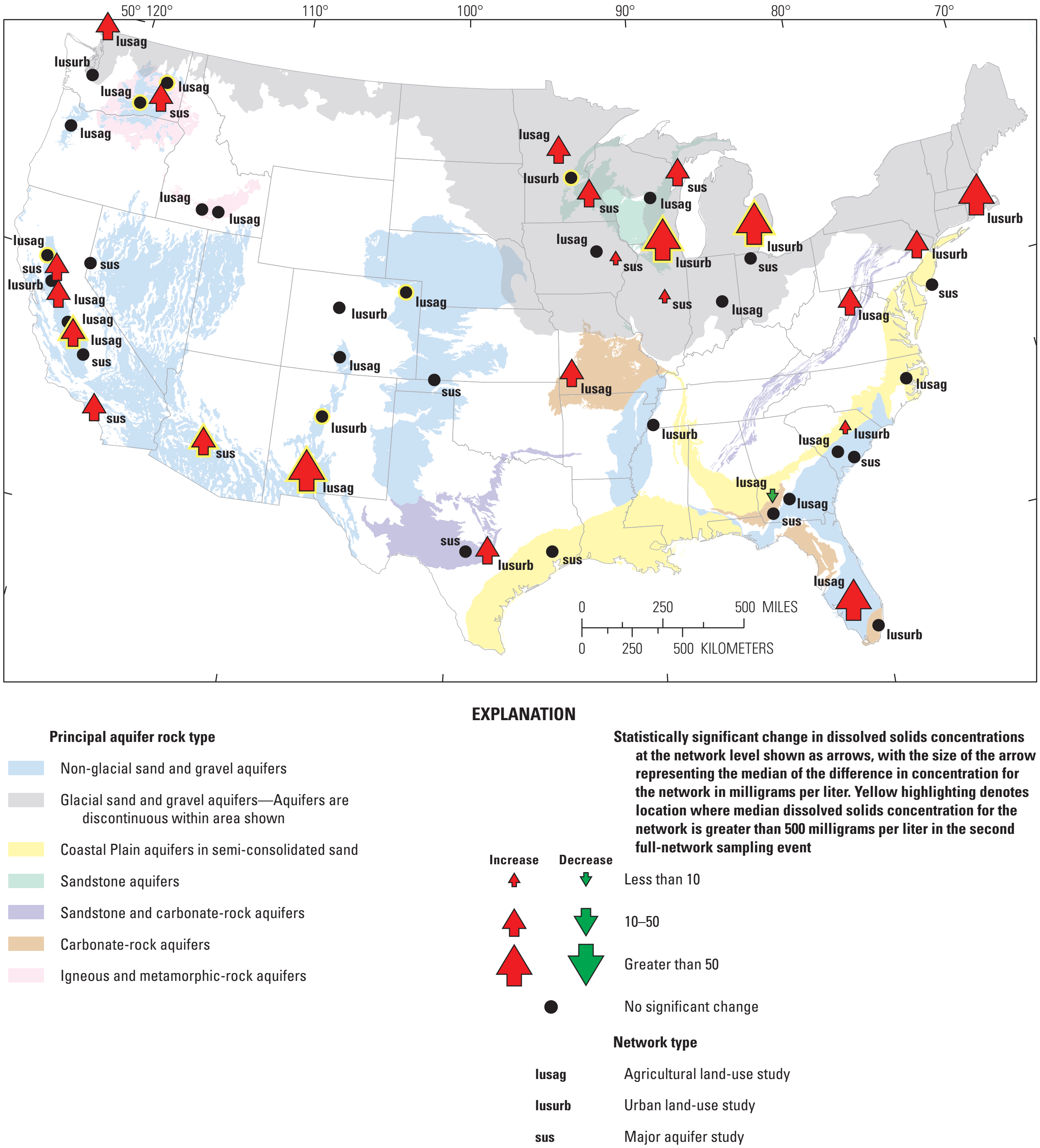


Figure 4. Locations of U.S. Geological Survey National Water-Quality Assessment Program well networks with and without statistically significant decadal-scale changes of dissolved solids concentrations in groundwater in the United States, 1988–2010, based on step-trend analysis of decadal data set using the Wilcoxon-Pratt signed rank test.

Table 4. Decadal-scale changes in nitrate concentrations in groundwater in the U.S. Geological Survey National Water-Quality Assessment Program well networks in the United States, 1988–2010, based on step-trend analysis of the decadal data set.

[NA, not applicable; shading indicates modified sign test was used instead of conventional sign test owing to tied pairs; **bold**, indicates statistically significant result at greater than a 90-percent confidence level; **(+)**, indicates a statistically significant increase in concentration at greater than a 90-percent confidence level; **(–)**, indicates a statistically significant decrease in concentration at greater than a 90-percent confidence level; mg/L as N, milligrams per liter as nitrogen]

Network name	Number of pairs of samples[1]	Number of tied pairs	Results of sign test, probability value	Results of Wilcoxon-Pratt signed-rank test, probability value[2]	Statistically significant result	Turnbull median change, in mg/L as N	Number of sites exceeding 10 mg/L as N: First full-network sampling event	Number of sites exceeding 10 mg/L as N: Second full-network sampling event	Probability value from Fischer's exact test
All networks combined	1,212	234	1.00	**<0.001**	(+)	**0.01**	143	176	**0.055**
acfbluscr3	19	0	**0.031**	**0.036**	(+)	**0.29**	1	2	1.00
acfbsus1	20	0	0.115	**0.067**	(+)	**0.32**	1	0	1.00
albelusag1	12	7	1.00	0.658		0.03	0	1	1.00
cazbsus1a	24	0	0.839	0.549		0.14	8	7	1.00
ccptlusag2b	16	0	0.804	0.877		-0.77	6	9	0.480
ccptlusor1b	19	0	1.000	0.601		0.05	2	5	0.405
ccptsus1b	30	3	0.604	0.382		0.02	1	1	1.00
dlmvluscr1	15	2	0.718	0.977		-0.10	3	4	1.00
dlmvsus1	23	9	0.509	**0.003**	(+)	**0.14**	1	7	**0.047**
eiwaluscr1	30	3	1.00	0.371		-0.02	11	15	0.435
eiwasus2	30	13	0.907	0.162		-0.04	4	3	1.00
gafluscr1	20	0	0.263	0.135		0.84	5	7	0.731
hpgwsus1a	30	0	0.362	0.453		0.01	1	2	1.00
lerilusrc1	29	8	0.536	**0.018**	(+)	**0.28**	1	2	1.00
lerisus1	27	23	1.00	0.327		0.01	0	0	NA
linjlusrc1	27	1	0.770	0.782		-0.09	0	1	1.00
linjsus2	24	4	0.862	0.240		-0.01	2	1	1.00
lirbsus1	29	17	0.932	[3]**0.005**	(–)	**-0.04**	0	0	NA
miselusrc1	20	3	0.176	**0.009**	(+)	**0.21**	0	0	NA
necblusrc1	21	2	0.142	0.056	(–)	-0.09	1	1	1.00
nvbrsus2	16	1	1.00	0.737		0.05	0	0	NA
ozrklusag2a	20	5	0.862	0.510		0.02	2	1	1.00
potolusag1	24	0	0.307	0.145		-0.09	6	3	0.461
pugtluscr1	19	1	0.266	0.324		1.1	12	12	1.00
pugtlusrs1	24	2	0.575	0.484		0.18	0	2	0.489
rioglusag1	25	2	0.763	0.788		0.13	5	7	0.742
riogluscr1	12	2	0.480	0.365		-0.11	2	2	1.00
rioglusrc1	10	3	0.752	0.276		0.05	0	0	NA
sacrluscr1	21	4	0.619	0.179		-0.04	0	0	NA
sacrlusrc1	18	5	0.862	0.217		-0.03	0	0	NA
sacrsus1	28	2	0.241	**0.046**	(+)	**0.14**	1	2	1.00

Table 4. Decadal-scale changes in nitrate concentrations in groundwater in the U.S. Geological Survey National Water-Quality Assessment Program well networks in the United States, 1988–2010, based on step-trend analysis of the decadal data set.—Continued

[NA, not applicable; shading indicates modified sign test was used instead of conventional sign test owing to tied pairs; **bold**, indicates statistically significant result at greater than a 90-percent confidence level; **(+)**, indicates a statistically significant increase in concentration at greater than a 90-percent confidence level; **(–)**, indicates a statistically significant decrease in concentration at greater than a 90-percent confidence level; mg/L as N, milligrams per liter as nitrogen]

Network name	Number of pairs of samples[1]	Number of tied pairs	Results of sign test, probability value	Results of Wilcoxon-Pratt signed-rank test, probability value[2]	Statistically significant result	Turnbull median change, in mg/L as N	Number of sites exceeding 10 mg/L as N: First full-network sampling event	Number of sites exceeding 10 mg/L as N: Second full-network sampling event	Probability value from Fischer's exact test
sanasus2	14	1	1.00	0.900		-0.05	0	0	NA
sanjluscr1a	18	1	0.405	**0.081**	(+)	**1.0**	5	6	1.00
sanjlusor1a	17	0	0.629	0.981		0.07	2	5	0.398
sanjlusor2a	19	0	0.359	0.355		0.62	7	12	0.194
sanjsus1	25	3	0.635	0.252		0.45	4	3	1.00
santluscr1	19	2	0.266	**0.095**	(–)	**-0.63**	9	6	0.508
santlusrc1	17	2	0.242	0.155		0.04	0	0	NA
santsus2	29	22	0.999	[3]**0.008**	(–)	**-0.05**	0	0	NA
sctxlusrc1	30	0	**0.018**	**0.003**	(+)	**0.36**	0	0	NA
sctxsus1	23	0	0.210	0.191		-0.04	0	0	NA
sofllusor1	17	10	0.982	0.285		-0.02	1	1	1.00
sofllusrc1a	17	11	0.995	0.301		0.02	0	0	NA
spltluscr1	29	0	**0.026**	**0.013**	(+)	**2.0**	13	16	0.600
trinsus3	16	12	1.00	1.000		0.00	0	0	NA
ucollusrc1	16	3	1.00	0.716		-0.03	0	0	NA
uirblusrc1	18	8	0.967	0.372		-0.01	0	0	NA
umisluscr1	22	2	0.194	0.205		0.88	9	10	1.00
umislusrc1	26	7	0.631	**0.046**	(+)	**0.04**	1	2	1.00
umissus3	22	5	0.485	0.327		-0.04	1	2	1.00
usnkluscr2	26	0	**0.078**	**0.025**	(+)	**0.26**	1	1	1.00
usnkluscr3	28	0	**0.089**	**0.038**	(+)	**0.06**	0	0	NA
whitluscr1	20	11	0.985	0.366		0.00	1	0	1.00
willlusag3	24	7	0.628	**0.045**	(–)	**-0.04**	1	0	1.00
wmiclusag2	26	1	0.482	**0.089**	(+)	**0.84**	10	13	0.577
wmicsus1	25	15	0.998	0.473		0.01	2	2	1.00

[1] Number of samples used for "all networks combined" calculations is not equal to the sum of the number of samples for individual networks. For "all networks combined" calculations, 13 samples with elevated reporting levels were excluded.

[2] Slightly different probability values resulted when using zero substitution for nondetects instead of the incremental difference substitution, but significance did not change.

[3] Statistically significant result, but more than half of the pairs were nondetects in both samples. Close scrutiny of data is advised.

a statistically significant change in nitrate concentrations (table 4) and were in agreement with results of the Wilcoxon-Pratt signed-rank test.

Results of the Wilcoxon-Pratt signed-rank test for data from all networks combined indicated a significant increase, with a median value of change in concentration of nitrate of 0.01 mg/L as N (table 4). The modified sign test, however, showed no significant change when used to evaluate the data from all networks combined. Results of the Fisher's exact test indicated that the number of wells exceeding the MCL of 10 mg/L as N increased in a statistically significant manner from the first sampling event to the second sampling event for all networks combined (table 4). Only one individual network, dlmvsus1 network in the Delmarva Peninsula, showed such an increase (table 4).

The geographic distribution of the patterns of change in nitrate concentrations based on the Wilcoxon-Pratt test results are shown in figure 5. Overall, the largest percentages of networks with statistically significant increases in nitrate concentrations were in agricultural or urban land-use studies rather than in major aquifer studies.

For most networks in this study, changes cannot be attributed to a specific cause; however, local and regional studies can provide insight on observed changes. For example, in the sctxlusrc1 (South-Central Texas) network, the statistically significant increase in nitrate concentrations is consistent with the known response of that aquifer to hydrologic conditions at the time samples were collected. Musgrove and others (2010) concluded that the increase in nitrate concentrations from the samples collected in 1998 (a relatively wet year) compared to 2006 (a relatively dry year) were consistent with a known hydrologic water-quality response where lower nitrate concentrations are associated with wetter conditions and higher nitrate concentrations are associated with dryer conditions. Thus the change in nitrate concentration, although statistically significant, cannot be interpreted as a long-term increasing trend in concentration in that network without further study.

Changes in Chloride, Dissolved Solids, and Nitrate by Network Type

Comparisons of decadal changes in chloride, dissolved solids, and nitrate concentrations by network type reveal several patterns (table 5). The percentage of networks with significant increases was greater than the percentage of networks with significant decreases in every network type for chloride, dissolved solids, and nitrate. There were fewer networks with statistically significant changes in nitrate concentrations than with changes in chloride or dissolved solids concentrations. This difference may occur because chloride and dissolved solids are typically conservative in that they typically do not react or degrade, whereas nitrate can degrade under reduction/oxidation (redox) geochemical conditions that are conducive to denitrification. Denitrification may suppress changes in nitrate concentrations in some settings. Lack of change in nitrate concentrations could also be due to a lack of change in inputs of nitrogen at land surface. A larger percentage of urban land-use networks had statistically significant increases in chloride, dissolved solids, and nitrate concentrations than agricultural land-use networks. No large differences were seen between percentages of networks with significant changes when land-use study networks with relatively shallow well depths were compared with the major aquifer study networks with deeper wells. In fact, the percentage of networks with statistically significant changes in dissolved solids and chloride was greater for major aquifer studies than for land-use studies.

Evaluation of Changes in Chloride, Dissolved Solids, and Nitrate Using Graphs and Maps, and Limits of Data

Understanding the results of changes in concentrations of chloride, dissolved solids, and nitrate requires evaluation beyond the results of statistical tests. Statistical results provide a numerical answer that is used to determine whether to accept or reject the hypothesis of the given test; however, to understand the test result or to answer questions of relevance to management of water resources, the statistical result (and validity of assumptions of the statistical tests) is only the first consideration. Additional important considerations include evaluation of the relevance of the magnitude of changes in concentration, examination of plots of changes in concentration, examination of maps showing the spatial distribution of changes, and limitations of the data sets.

The magnitude of concentration change may differ in importance, detectability, and spatial distribution for chloride, dissolved solids, or nitrate in a given network. For example, the median change in nitrate concentration of 1 mg/L as N of nitrate in the sanjluscr1a (San Joaquin-Tulare Basins) network has different implications than the median change in the chloride concentration of 1 mg/L in the linjsus2 (Long Island-New Jersey Coastal Drainages) network because concentration ranges for nitrate are typically lower than the ranges for chloride (appendix 1, available as separate file). Also 1 mg/L of nitrate as N represents a much larger percentage of the nitrate MCL than 1 mg/L of chloride represents as a percentage of the chloride SMCL.

Although the Turnbull median is a general measure of overall change in concentration in a network, the Turnbull estimator does not account for spatial differences in concentration change in a network or aquifer and should be interpreted with caution. Plots of the differences in concentration can be used to evaluate the distribution of all changes in concentration. A Turnbull median change of a small magnitude that is a result of an equally large shift in concentration in both directions would have different implications than a Turnbull median change of a small magnitude that is a result of an overall small shift in concentration. For example, the Turnbull median change in the hpgwsus1a (High Plains Regional Groundwater Study) network of small magnitude (increase of 0.01 mg/L

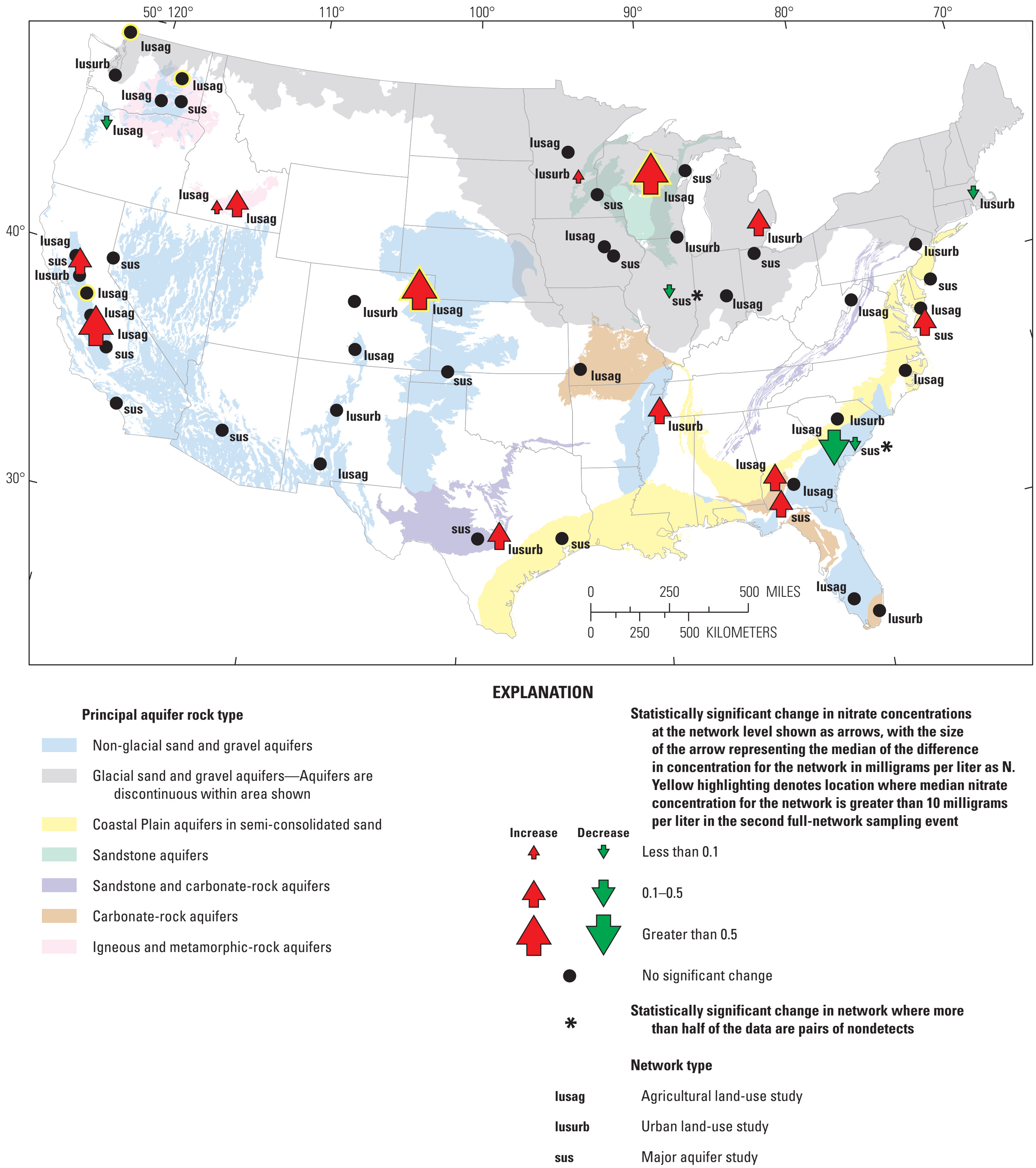


Figure 5. Locations of U.S. Geological Survey National Water-Quality Assessment Program well networks with and without statistically significant decadal-scale changes of nitrate concentrations in groundwater in the United States, 1988–2010, based on step-trend analysis of decadal data set using the Wilcoxon-Pratt signed rank test.

Table 5. Summary of statistical results of the Wilcoxon-Pratt test, for decadal-scale change in concentrations of chloride, dissolved solids, and nitrate in groundwater, by network type, in the U.S. Geological Survey National Water-Quality Assessment Program well networks in the United States, 1988–2010.

[Results are considered statistically significant at the 90-percent confidence level.]

	Number of networks	Number of networks with statistically significant changes	Percentage of networks with statistically significant changes	Number of networks with increase	Number of networks with decrease	Percentage of networks with increase	Percentage of networks with decrease
Chloride							
All networks	56	26	46	24	2	43	4
All land-use studies	38	15	39	14	1	37	3
Agriculture only	25	8	32	7	1	28	4
Urban only	13	7	54	7	0	54	0
Major aquifer studies	18	11	61	10	1	56	6
Dissolved solids							
All networks	54	23	43	22	1	41	2
All land-use studies	37	15	41	14	1	38	3
Agriculture only	24	9	38	8	1	33	4
Urban only	13	6	46	6	0	46	0
Major aquifer studies	17	8	47	8	0	47	0
Nitrate							
All networks	56	18	32	13	5	23	9
All land-use studies	38	13	34	10	3	26	8
Agriculture only	25	8	32	6	2	24	8
Urban only	13	5	38	4	1	31	8
Major aquifer studies	18	5	28	3	2	17	11

as N of nitrate; table 4) was a result of generally equally large shifts in concentration in both directions (fig. 6), and thus, the network overall was determined to have no statistically significant change. These concentration changes can be interpreted differently than the Turnbull median change of small magnitude (decrease of 0.04 mg/L as N of nitrate; table 4) that was a result of an overall small shift in concentration in the lirbsus1 (Lower Illinois Basin) network (fig. 7).

Plotting the changes in concentrations of nitrate for individual pairs can enhance the understanding of the results of the Wilcoxon-Pratt signed-rank test, as noted above. The plots in figure 6 are examples of the change in nitrate concentrations from the first sampling event to the second sampling event (sample 2 – sample 1) for each well in three networks and are selected to illustrate cases where the predominant direction and magnitude of change are in accordance with, and reinforce, the statistical results. Wells are ordered from largest decrease to largest increase. Symbols to the left of the zero line (in green) in each plot indicate a decrease in nitrate concentrations; symbols to the right of the center line (in red) indicate an increase in nitrate concentrations. As previously discussed, nitrate concentrations in the hpgwsus1a (High Plains Regional Groundwater Study) network generally increased and decreased similar amounts with a large number of samples changing by a very small amount, resulting in no statistically significant change for this network. In the sanjluscr1a (San Joaquin-Tulare Basins) network, nitrate concentrations in about one-third of the wells decreased, and nitrate concentrations in about two-thirds of the wells increased. The Wilcoxon-Pratt signed-rank test resulted in a p-value of 0.08, indicating a statistically significant increase in nitrate concentrations in the sanjluscr1a network, and there was also a large increase in the Turnbull median (1.0 mg/L as N). Although not all pairs in the sanjluscr1a network had increases in nitrate concentrations, more had increases than decreases, and the magnitude of the increases outweighed the magnitude of the decreases. The plot of data from the spltluscr1 (South Platte River Basin) network (fig. 5) also supports the Wilcoxon-Pratt signed-rank test finding of statistically significant increases in nitrate concentrations, with more than two-thirds of the wells having increased nitrate concentrations and a large median change.

Plots of the change in concentrations can be used to identify well networks where additional analysis may be warranted, especially for nitrate because it has frequent occurrences of concentrations reported as less than values (nondetects). Figure 7 shows plots for two well networks (lirbsus1 and santsus2) where more than half the sample pairs were nondetects in both sampling events and the modified sign test and the Wilcoxon-Pratt signed-rank tests gave extremely different p-values. Large numbers of pairs of nondetects and disagreement among statistical results were indications that results from that well network may need closer scrutiny. In this plot, if nitrate was detected in the first sampling event and the second sampling event, the difference is a specific value, and a dot is shown for that well. A horizontal line is shown in figure 7 when one or both samples were nondetects; the length of the line is determined by the range of possible values. If both of the samples were nondetects, a horizontal (black) line crosses zero, and the bar ranges from the first reporting level to the second reporting level; for the paired values of less than 0.05, less than 0.06, the left end of the line is at -0.05, and right end of line is at +0.06. If one case is a nondetect and the other case is a reported value with the same reporting limit, the horizontal line terminates at 0, and the other end of the line has a value equal to the reporting limit; for the paired values of 0.06, less than 0.06, the left end of line is at -0.06 and right end of line is at 0. Any horizontal range line that spans or includes zero is colored black, indicating uncertainty as to whether there is an actual increase or decrease in concentration. If the pair has a nondetect and a reported value, the end of the line farther from zero is the detected value, and the length of the line is equal to the value of the reporting limit of the other sample; for the paired values of 0.09, less than 0.06, the left end of line is at -0.09, and right end of line is at -0.03. The nondetect makes the true difference uncertain; however, it is known that the difference is a decrease, so it is colored green. The paired values of less than 0.05, 0.194 are represented with a line from 0.144 to 0.194. This is also a case where the true difference is uncertain, but the difference is known to be an increase; thus, it is colored red. The color of the line is red to represent a known increase or green to represent a known decrease in concentration. The point of the plots on figure 7 is that, despite a statistically significant result for all three of those networks, graphing the data in this manner illustrates the amount of uncertainty in the results.

The lirbsus1 (Lower Illinois River Basin) network had 17 pairs of nondetects. In 11 other pairs, one of the samples in the pair was a nondetect, and the other was a reported value (7 of which represent a known decrease from the first sampling event to the second sampling event). In one case, both samples were reported values (this pair represents an increase between the first sampling event and the second sampling event). Results of the Wilcoxon-Pratt signed-rank test indicate a significant change (decrease) for this network (p-value = 0.005). However, from figure 7, it is evident that the magnitude of change in this network is very small (note the scale on the x-axis is very small). The low p-value is affected by several pairs that changed from detects to nondetects, but this may not constitute a practical or meaningful change in concentrations. Similarly, the santsus2 network had 22 pairs of nondetects and 7 samples with known nonzero differences (fig. 6), but the Wilcoxon-Pratt signed-rank test calculated a p-value of 0.008. The magnitude of change in both of these networks is very small. Examination of the data and figure 7 reveals the large amount of uncertainty as to the actual concentration differences in these cases. Theoretically, more than one-half of the data in these networks could be either all increases or all decreases, even though they were treated as ties in the statistical analysis. Networks for which more than one-half of the data had tied differences (paired nondetects) and for which the modified sign test and the Wilcoxon-Pratt signed-rank tests had very different p-values are footnoted in table 4 and given a different symbol in figure 5 in order to encourage close scrutiny of these networks when evaluating the relevance of the finding that the network had a statistically significant change in concentration. The issue of paired nondetects affected only the nitrate analysis; there were no such cases in the chloride and dissolved solids data sets. It is noteworthy to point out that the Wilcoxon-Pratt signed-rank test does in fact account for tied pairs when calculating the test statistic; however, the test is not able to discern whether pairs of nondetects entered as “ties” in the statistical program are in fact the same value, nor does the test indicate whether a statistically significant change is of a magnitude that has any practical meaning.

The previous paragraph explains the importance of looking at the plots and measures of change to enhance the understanding of the statistical results. This level of analysis can be used to determine the practical relevance of a given statistical result. Plots illustrating concentration differences for chloride, dissolved solids, and nitrate are available for every network online at *http://water.usgs.gov/nawqa/studies/gwtrends/*.

Maps illustrating changes in concentration can be used to evaluate spatial patterns of changes in concentrations and to evaluate locations of wells with extreme changes in concentration (outliers). Examination of maps is important, as it may indicate geographical patterns not evident in the statistical results for that network. A network could have a statistical result of no significant change but have a small number of samples in one area with increased concentrations. This potentially important information would be visible on a map, although the statistical result indicated no significant change. In addition, networks with significant changes may not have an even distribution of results. For example, the network dlmvsus1 (Delmarva Peninsula) had a statistically significant increase in nitrate concentrations. However, a map of changes in concentration (fig. 8) illustrates that many of the wells that did not have changes in concentrations were in the southern part of the network, and in fact, many were nondetects in both cases. Wells that had increases in concentrations were common in the central to northern part of the network. There may be a number of explanations for this pattern, but the pattern would not be evident without looking at the map. Also, the network potolusag1 (Potomac River Basin) had a significant increase in concentrations of dissolved solids, but the map (fig. 9) illustrates that the pattern seems to change from north to south. The highest increases in concentration are in the north, and decreases in concentrations and lower

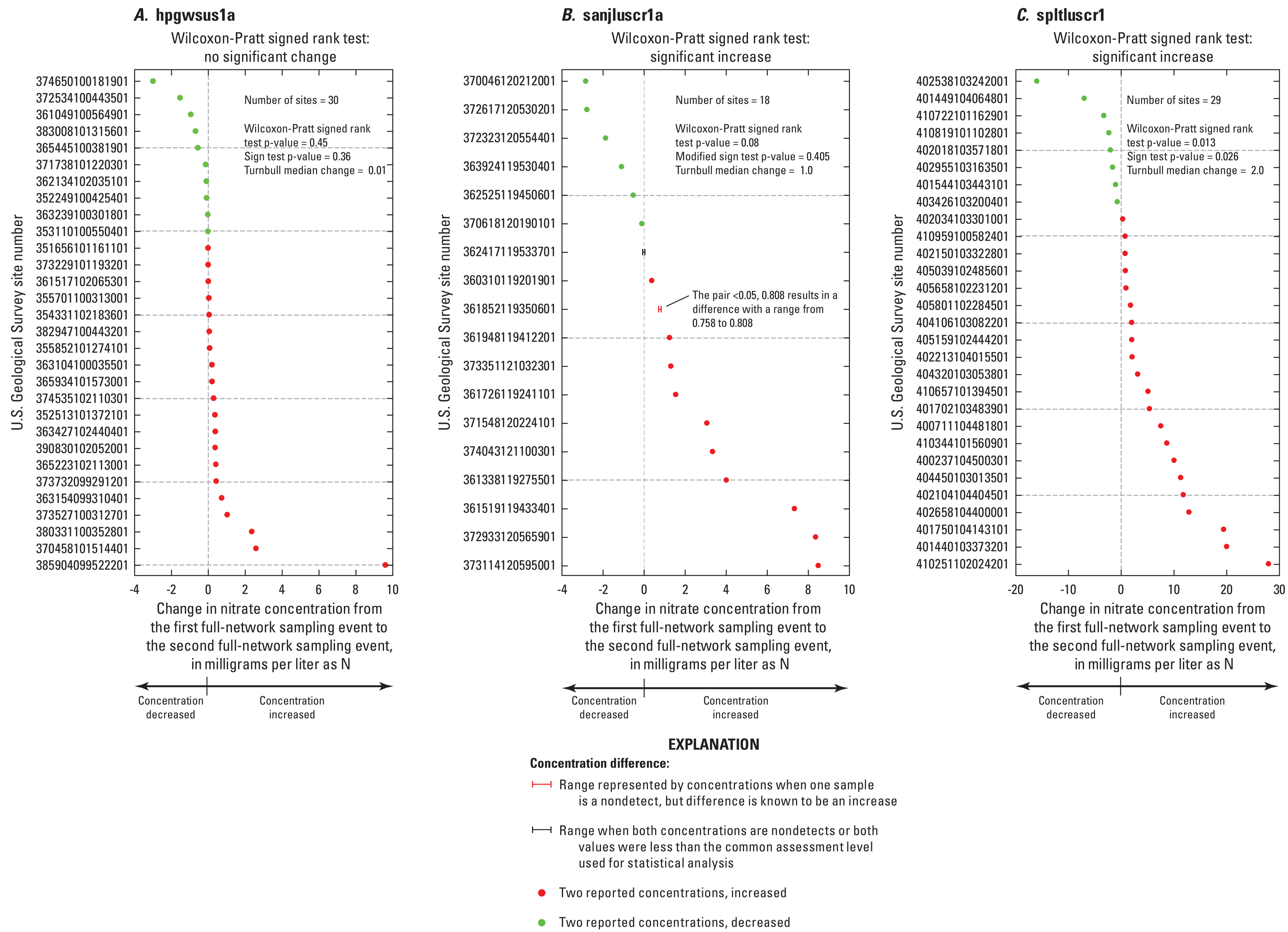


Figure 6. Change in nitrate concentrations in groundwater between the first full-network sampling event and the second full-network sampling event in U.S. Geological Survey National Water-Quality Assessment Program well networks, *A*, hpgwsus1a (High Plains Regional Groundwater Study), *B*, sanjluscr1a (San Joaquin-Tulare Basins), and *C*, spltluscr1 (South Platte River Basin) in the United States, 1988–2010. (<, less than)

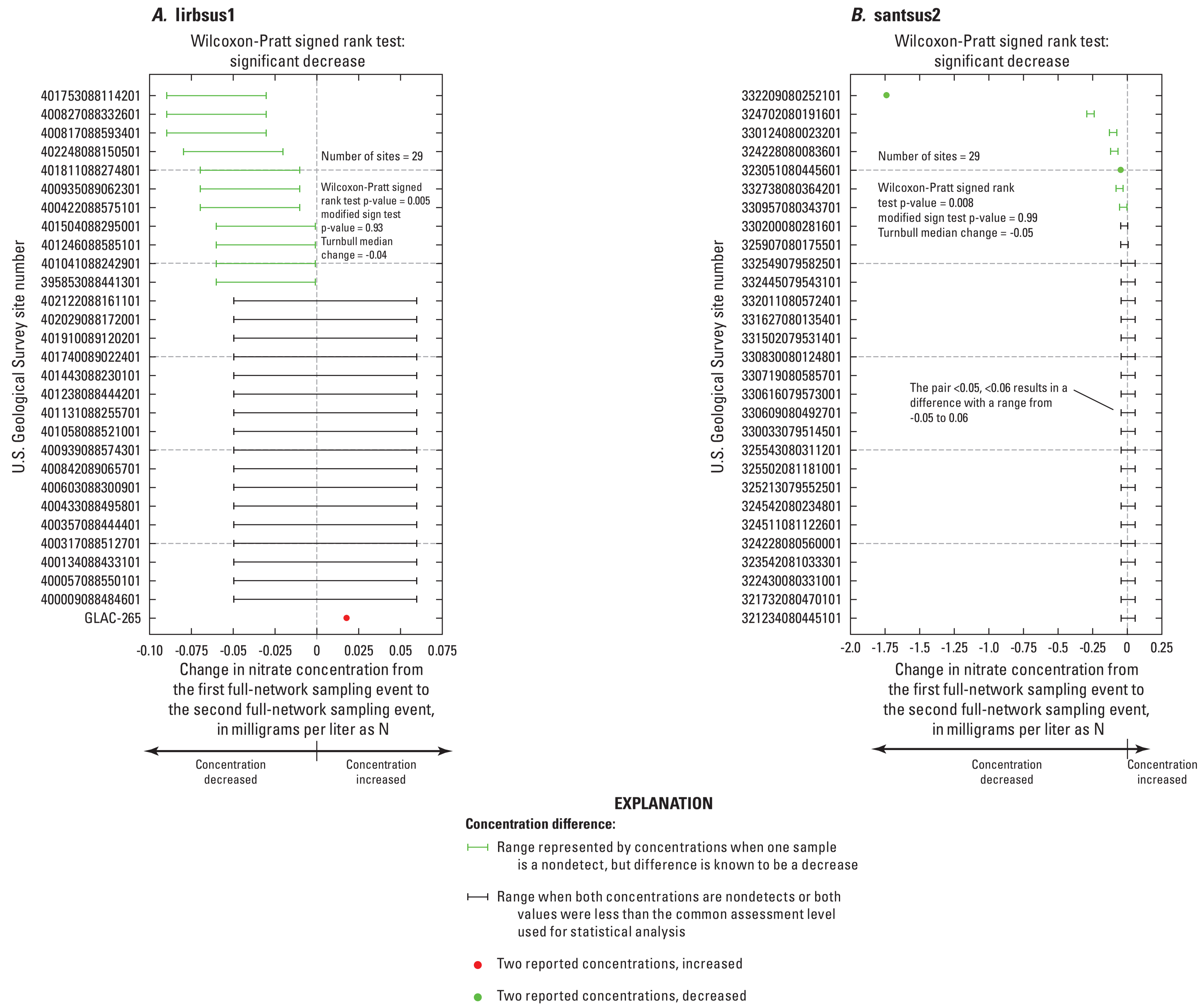
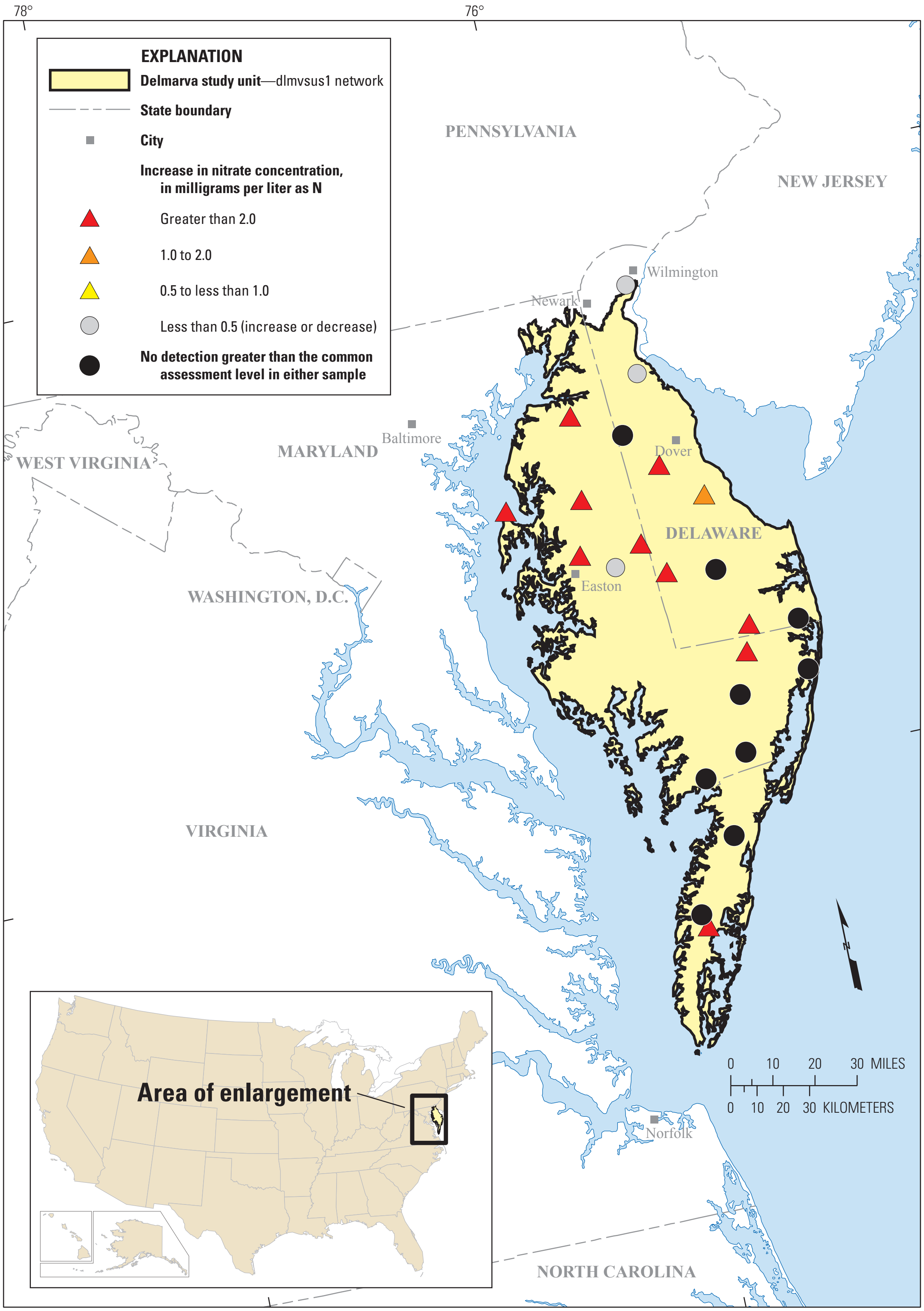


Figure 7. Change in nitrate concentrations in groundwater between the first full-network sampling event and the second full-network sampling event in U.S. Geological Survey National Water-Quality Assessment Program well networks, *A*, lirbsus1 (Lower Illinois River Basin) and, *B*, santsus2 (Santee River Basin and Coastal Drainages) in the United States, 1988–2010. (<, less than)



Base from U.S. Geological Survey 1:2,000,000 digital data
Albers Equal-Area Conic projection, standard parallels 29°30' and 45°30', central meridian -96°, latitude of origin 23°

Figure 8. Locations of, and decadal-scale changes in, nitrate concentrations in groundwater in U.S. Geological Survey National Water-Quality Assessment Program well network dlmvsus1 (Delmarva Peninsula) in the United States, 1988–2010.

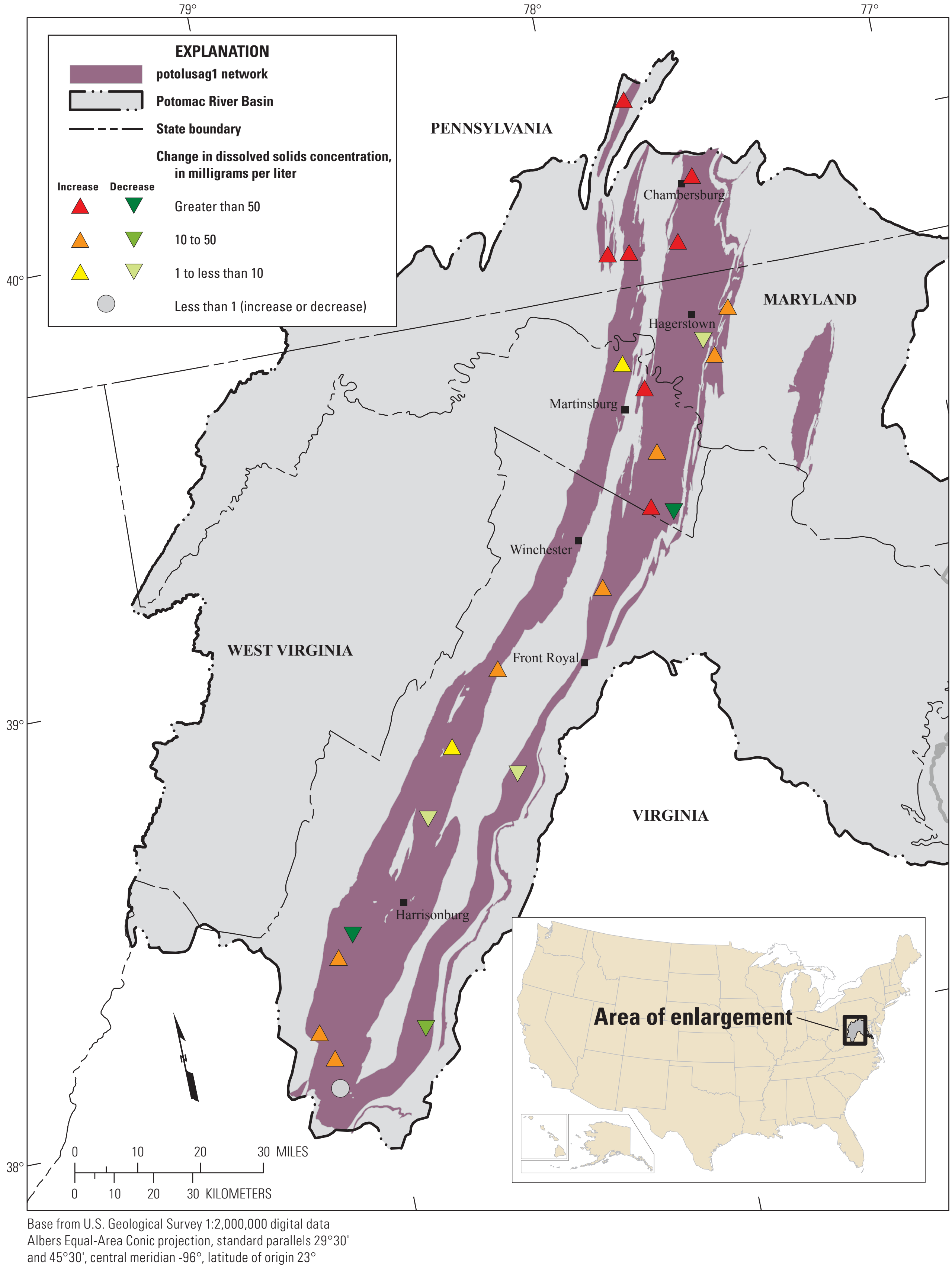


Figure 9. Locations of, and decadal-scale changes in, dissolved solids concentrations in groundwater in U.S. Geological Survey National Water-Quality Assessment Program well network potolusag1 (Potomac River Basin) in the United States, 1988–2010.

magnitude increases are found farther south. All of the wells with increases in dissolved solids concentrations greater than 50 mg/L are in West Virginia and Pennsylvania. Although the pattern may be related to issues such as population density or other issues not related to the state boundaries, it is also possible that management practices leading to these patterns differ among the States of Virginia, West Virginia, Maryland, and Pennsylvania. This question would not arise without an examination of the data in map form. Maps for every network are available at *http://water.usgs.gov/nawqa/studies/gwtrends/*.

In addition to the considerations, discussed above, that are related to the interpretation of statistical results of the test for change based on paired observations collected about 10 years apart, other factors related to representativeness of the data need to be considered. Hydrologic conditions that affect water quality may differ during periods of sample collection even within each sampling cycle. In some study units, water quality may not be adequately characterized by the number of wells sampled.

Changes in Concentrations Based on Time-Series Analysis of the Biennial Data Set

Although the step-trend analysis is the primary indicator of changes in groundwater quality, these data are supplemented by a more frequent biennial (every other year) sampling at a subset of four to five wells in each network. Time-series analysis of the biennial data can illustrate whether or not changes seen in the step-trend analysis of the decadal data set are continuous on a smaller time scale and may also illustrate the time at which trend reversals may have occurred. The results also can be used to estimate the rate of change in concentrations of chloride, dissolved solids, or nitrate. Direct comparisons between step-trend analysis of the decadal data from the full well networks and time-series analysis of the biennial data need to be qualified. The wells in the biennial data set may be affected by site-specific conditions not present in the other network wells. The biennial data covers a smaller area and, in many cases, a different time period than the decadal data. The results of the biennial analysis are shown by network, but it is important to remember that these results are for a subset of four or five wells from the larger network.

Chloride

Of the 52 networks with sufficient samples for time-series analysis of chloride concentrations in groundwater using the Regional Kendall test, 23 networks had statistically significant changes—17 with increased concentrations and 6 with decreased concentrations (table 6, at end of report). Land-use studies had a larger proportion of networks with statistically significant changes than major aquifer studies, and urban land-use studies had the largest percentage of the networks with increased concentrations (50 percent). Although major aquifer studies had a lower percentage of networks with significant changes, all of the significant changes in major aquifer studies involved increased concentrations (table 6).

Six networks had statistically significant changes and increases in chloride concentrations that were greater than 0.5 mg/L/yr (table 6). Four of these six networks were in urban land-use studies. The uirblusrc1 (Upper Illinois River Basin) network had the largest annual increase in chloride concentration of 22 mg/L/yr; this network had the largest increase in chloride concentrations in the decadal-scale sampling as well. Two agricultural land-use networks (ccptlusag2b and ccptlusor1b, both in the Central Columbia Plateau-Yakima River Basin) had statistically significant decreases in chloride concentrations that were greater than 0.5 mg/L/yr (table 6).

Dissolved Solids

Of the 50 networks with samples for time-series analysis of dissolved solids concentrations in groundwater using the Regional Kendall test, 21 networks had statistically significant changes (table 7, at end of report). Seventeen networks had significant increases, and four had significant decreases. Urban land-use studies and major aquifer studies had a larger percentage of networks with significant changes than agricultural land-use studies.

Nine networks had statistically significant changes and changes in concentrations of dissolved solids that were greater than 4 mg/L/yr (table 7). Eight of the nine networks had increases, and of the eight with increases, four networks were in northeastern or midwestern urban land-use studies. The other four networks were in agricultural land-use studies in the central valley of California. The largest annual change was an increase of 33 mg/L/yr for the biennial subset of the uirblusrc1 (Upper Illinois River Basin) network, which also had the largest rate of change (estimated by the Turnbull median change of 160 mg/L) in the decadal data set for that network (table 3). The largest annual decrease was for the ccptlusor1b (Central Columbia Plateau–Yakima River Basin) network, in the Pacific Northwest, which had a statistically significant decrease in dissolved solids, with a rate of change of -7.5 mg/L/yr.

Nitrate

Fifty-two networks had sufficient numbers of samples for time-series analysis of nitrate concentrations in groundwater using the Regional Kendall test. Of these 52 networks with biennial data, more than twice as many networks had statistically significant increases in nitrate concentrations (13) than had statistically significant decreases in nitrate concentrations (6) (table 8, at end of report).

Four networks had statistically significant changes and annual increases in nitrate concentrations of more than 0.1 mg/L/yr as N (table 8). Three of these four networks were agricultural land-use studies in the San Joaquin Valley, and one was an urban land-use study in the Upper Mississippi River Basin. Three other networks, also all agricultural land-use studies, had statistically significant changes and decreases in nitrate concentrations of more than 0.1 mg/L/yr as N (table 8). In general, wells in land-use studies have shallower depths than wells in major aquifer studies and are, thus, possibly more sensitive to changes over short time periods, especially those wells that might be related to varying agricultural practices, such as changes in crops or fertilizer use.

In one network, wmiclusag2 (Western Lake Michigan Drainages), the step-trend analysis of decadal data for nitrate indicated a significant change in one direction (increase), whereas the time-series analysis of biennial data showed a significant change in the opposite direction (decrease). As illustrated by figure 10, although the overall network of 26 wells had a significant increase in nitrate concentrations from the first sampling event to the second sampling event, only a single well (USGS site number 435339089305001) of the five in the biennial data set had an increase in nitrate concentrations over that same period. This may indicate that, for this network, the biennial data subset does not reflect conditions elsewhere in the full network data set. Also, this plot shows that nitrate concentrations in several of the wells in the biennial data set began to decrease after the second full-network sampling event. This decrease in concentrations in the biennial data set after the second sampling event may provide advance indications that the next round of sampling may reveal decreased concentrations at the network level. The comparison of step-trend analysis and time-series analysis may be helpful in the long run in understanding the timing of trend reversals and the amount of temporal variability in concentrations, but as was the case with the other statistical results, careful scrutiny of plots is needed to understand the meaning of the statistical results.

Summary and Conclusions

Groundwater-quality data collected by the U.S. Geological Survey National Water-Quality Assessment Program (NAWQA) were analyzed to evaluate decadal-scale changes in chloride, dissolved solids, and nitrate concentrations in groundwater at the national and well-network scale. Samples of groundwater were collected from wells in networks from 1988 through 2000; the same networks and wells were resampled from 2001 through 2010. The data set consists of samples from 1,235 wells in 56 well networks, representing major aquifer and urban and agricultural land-use study networks with analytical results on a decadal-scale time period. The Wilcoxon-Pratt signed-rank test is the primary statistical test used to evaluate decadal-scale changes in concentrations. The median of the difference in concentrations at the network level, calculated using the Turnbull method, was used to indicate the magnitude of decadal-scale changes in concentrations. The sign test or modified sign test was used as a supplemental indicator of decadal-scale changes in concentrations. A proportion's test (the Fischer's exact test) was used to evaluate whether or not a shift had occurred in the proportion of samples that exceeded a regulatory threshold. A subset of four to six wells in each network was sampled biennially to allow for a time-series analysis of concentrations using the Regional Kendall's test.

The results of the statistical analysis of chloride showed that 43 percent of the networks had a statistically significant increase in chloride concentrations, whereas only 4 percent of the networks had a statistically significant decrease. Five networks had median increases in concentrations greater than 20 mg/L, and one network had an increase in median concentrations of 67 mg/L. The sign test results show that, for 32 percent of the networks, concentrations of chloride increased, and for 4 percent of the networks, concentrations of chloride decreased. No networks had a statistically significant shift in the proportion of wells with chloride exceeding the USEPA SMCL of 250 mg/L during the study period.

The results of the Wilcoxon-Pratt signed-rank test for dissolved solids show that 41 percent of the networks had statistically significant increases, and 2 percent had statistically significant decreases. The magnitude of change was large in some cases. Five networks had median increases of greater than 50 mg/L, and one had a median increase of 260 mg/L. The sign test results indicate that 26 percent of the networks had significant increases in dissolved solids, and the results are generally in agreement with the results of the Wilcoxon-Pratt signed-rank test. The evaluation of dissolved solids data for all networks combined showed a statistically significant shift in the proportion of wells exceeding the SMCL of 500 mg/L, although no statistically significant shifts were indicated for individual networks.

The results of the Wilcoxon-Pratt signed-rank test show that 23 percent of the networks had statistically significant increases in nitrate concentrations, whereas 9 percent had statistically significant decreases; the remaining 68 percent showed no change. In general, the magnitude of change in those networks with increases was larger than the magnitude of change in those networks with decreases. Networks with decreased nitrate concentrations generally had low concentrations of nitrate at the beginning of sampling. The results of the sign test indicate fewer significant changes than were indicated by the Wilcoxon-Pratt signed-rank test, which is to be expected because the sign test is a less sensitive measure of change. Changes in nitrate concentrations can be affected by geochemical processes, such as denitrification, which may mask long-term changes in concentrations of nitrate caused by changes in loading, unlike chloride and dissolved solids which have no similar processes and tend to be conservative. Also, for all networks combined, the proportion of samples exceeding the USEPA MCL of 10 mg/L as N for nitrate increased significantly during the sampling period.

A large majority of the networks (71 percent) showed statistically significant changes for at least one of the three indicators of water quality evaluated. Although 43 percent, 41 percent, and 23 percent of networks had statistically significant increases in concentrations of chloride, dissolved solids, or nitrate, respectively, 66 percent of the networks had a statistically significant increase in at least one of these indicators.

Agricultural land-use studies had lower percentages of networks with statistically significant increases in chloride and dissolved solids concentrations than the urban land-use or major aquifer networks. It is noteworthy, however, that the networks with statistically significant increases in nitrate concentrations and relatively large median changes in concentrations were in agricultural land-use studies. Major aquifer studies are represented by wells that tended to be deeper than the wells in the land-use studies and, therefore, could be expected to be slower to exhibit water-quality changes resulting from changes at the land surface than wells in the land-use studies. Nevertheless, the major aquifer study networks had a similar number of networks with statistically significant changes when compared to the two types of land-use studies.

Because of differences in the data sets and statistical tests, the results of the Wilcoxon-Pratt signed-rank test on the decadal-scale data and the Regional Kendall test on the biennial data are not directly comparable. Nevertheless, the results of the analysis of the biennial sampling subset of wells generally support the findings of the decadal analysis. Typically, more networks had increased concentrations than decreased concentrations, and the magnitude of change was, in general, greater for networks with increased concentrations. One general tendency in the biennial sampling subset for chloride and dissolved solids was that, if the results of the step-trend analysis had a strong statistical relation (low p value), the time-series analysis was likely to have a strong statistical relation as well. This pattern was not evident for nitrate. In only 1 case out of a possible 154, analytical results for the biennial sampling subset were the opposite of the results of the decadal analysis; in that case, graphical analysis indicates that the trend reversal likely occurred after the second full-network sampling event. The results of the biennial sampling subset can be used to understand temporal variability and responses to various factors that drive change.

Results of the statistical tests for changes in chloride, dissolved solids, and nitrate concentrations in groundwater are for each network as a whole. However, the interpretation of the statistical results needs to include consideration of the relevance of the magnitude of changes in concentration, examination of maps showing the spatial distribution of changes, and limitations of the data sets.

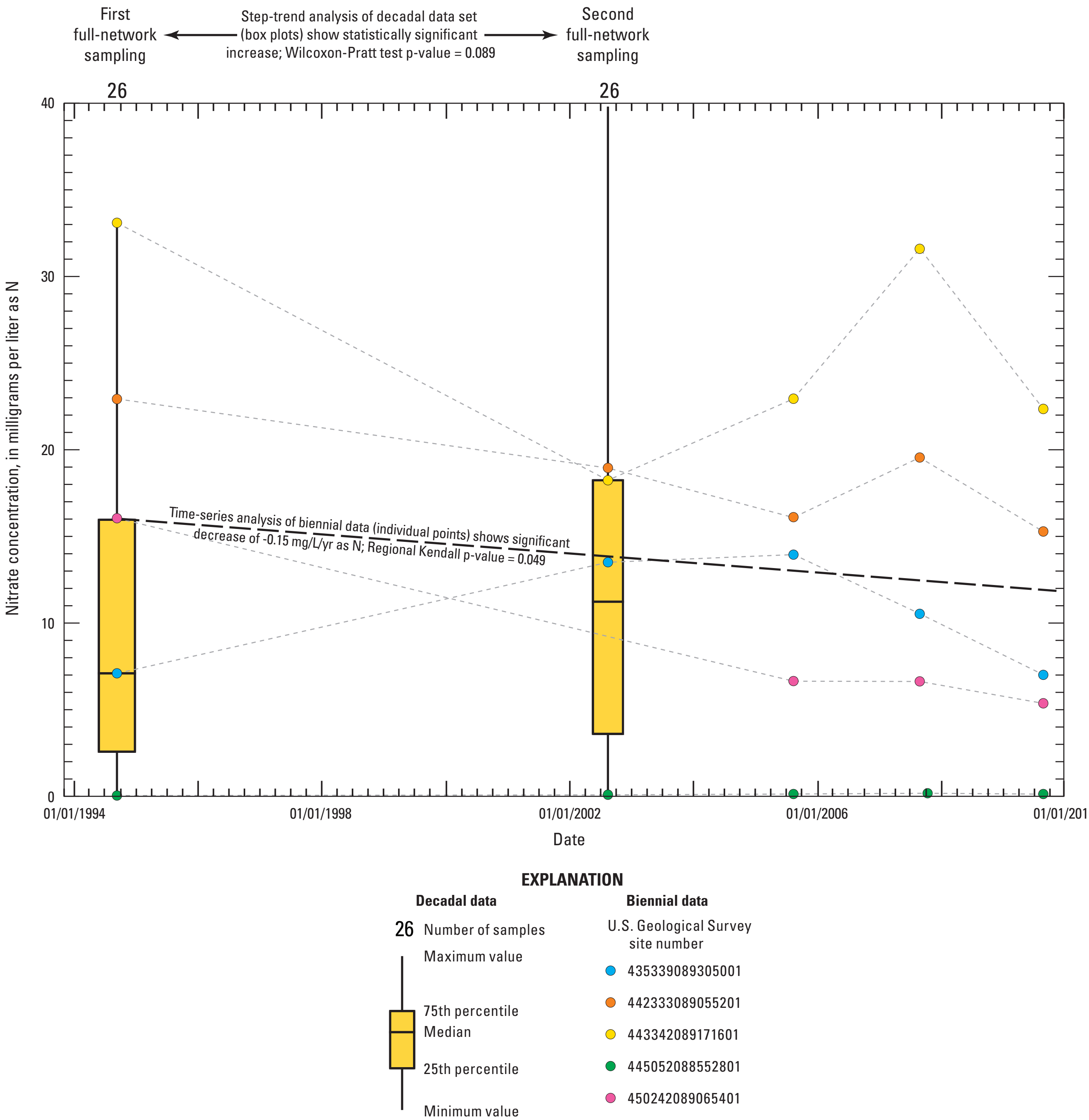


Figure 10. Boxplots of nitrate concentrations from both full-network sampling events and nitrate concentrations for five individual wells sampled biennially in the U.S. Geological Survey National Water-Quality Assessment Program well network wmiclusag2 (Western Lake Michigan Drainages) in the United States, 1988–2010.

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Tables 1, 6, 7, and 8

Table 1. Description of U.S. Geological Survey National Water-Quality Assessment Program networks analyzed for decadal-scale changes in chloride, dissolved solids, and nitrate in groundwater representing principal aquifers in the United States, 1988–2010.

[NA, not applicable; Network type: urb = urban land-use study; ag = agricultural land-use study; sus = major aquifer study]

Network name	Study unit code	Study unit name	Principal aquifer[1]	Aquifer rock type[1]	Network type	First full-network sampling event	Second full-network sampling event	Span between sampling (years)	Number of samples: Chloride	Number of samples: Dissolved solids	Number of samples: Nitrate	Median well depth, in feet	Land use from 2001[2]: Median percent agricultural land use	Land use from 2001[2]: Median percent urban land use
			All networks combined			1988–2000	2001–2010	NA	1,227	1,184	1,225	65	60	1
acfbluscr3	ACFB	Apalachicola-Chattahoochee-Flint River Basin	Floridan aquifer system/ surficial aquifer system	Carbonate-rock aquifers/ non-glacial sand and gravel aquifers	ag	1993	2002	9	19	19	19	48	74	0
acfbsus1	ACFB	Apalachicola-Chattahoochee-Flint River Basin	Floridan aquifer system	Carbonate-rock aquifers	sus	1994	2002	8	21	21	20	125	56	0
albelusag1	ALBE	Albemarle-Pamlico Drainage Basin	Surficial aquifer system	Non-glacial sand and gravel aquifers	ag	1994–95	2002	8	12	12	12	11	65	0
cazbsus1a	CAZB	Central Arizona Basins	Basin and Range basin-fill aquifers	Non-glacial sand and gravel aquifers	sus	1996–97	2008	12	24	24	24	404	4	2
ccptlusag2b	CCYK	Central Columbia Plateau-Yakima River Basin	Columbia Plateau basin-fill aquifers	Non-glacial sand and gravel aquifers	ag	1993	2002	9	16	16	16	44	93	3
ccptlusor1b	CCYK	Central Columbia Plateau-Yakima River Basin	Columbia Plateau basin-fill aquifers	Non-glacial sand and gravel aquifers	ag	1994–95	2002	8	19	19	19	29	93	1
ccptsus1b	CCYK	Central Columbia Plateau-Yakima River Basin	Columbia Plateau basin-fill aquifers/Columbia Plateau basaltic-rock aquifers	Non-glacial sand and gravel aquifers/igneous and metamorphic-rock aquifers	sus	1994	2002	8	30	30	30	223	31	9
dlmvluscr1	PODL	Potomac River Basin and Delmarva Peninsula	Northern Atlantic Coastal Plain aquifer system	Coastal Plain aquifer systems in semiconsolidated sand	ag	1988	2001	13	16	0	15	21	60	0
dlmvsus1	PODL	Potomac River Basin and Delmarva Peninsula	Northern Atlantic Coastal Plain aquifer system	Coastal Plain aquifer systems in semiconsolidated sand	sus	1988	2001	13	23	0	23	43	54	1
eiwaluscr1	EIWA	Eastern Iowa Basins	Glacial aquifer system	Glacial sand and gravel aquifers	ag	1997	2007	10	30	30	30	18	93	1
eiwasus2	EIWA	Eastern Iowa Basins	Glacial aquifer system	Glacial sand and gravel aquifers	sus	1998	2007	9	30	30	30	54	81	2

Table 1. Description of U.S. Geological Survey National Water-Quality Assessment Program networks analyzed for decadal-scale changes in chloride, dissolved solids, and nitrate in groundwater representing principal aquifers in the United States, 1988–2010.—Continued

[NA, not applicable; Network type: urb = urban land-use study; ag = agricultural land-use study; sus = major aquifer study]

Network name	Study unit code	Study unit name	Principal aquifer[1]	Aquifer rock type[1]	Network type	First full-network sampling event	Second full-network sampling event	Span between sampling (years)	Number of samples			Median well depth, in feet	Land use from 2001[2]	
									Chloride	Dissolved solids	Nitrate		Median percent agricultural land use	Median percent urban land use
gaflluscr1	GAFL	Georgia-Florida Coastal Plain	Surficial aquifer system	Non-glacial sand and gravel aquifers	ag	1994	2002	8	20	20	20	30	70	0
hpgwsus1a	HPGW	High-Plains Regional Groundwater Study	High Plains aquifer	Non-glacial sand and gravel aquifers	sus	1999	2010	11	30	29	30	293	45	0
lerilusrc1	LERI	Lake Erie-Lake Saint Clair Drainages	Glacial aquifer system	Glacial sand and gravel aquifers	urb	1996–97	2006	10	29	29	29	25	25	39
lerisus1	LERI	Lake Erie-Lake Saint Clair Drainages	Glacial aquifer system	Glacial sand and gravel aquifers	sus	1998	2007	9	27	27	27	90	89	0
linjlusrc1	LINJ	Long Island-New Jersey Coastal Drainages	Northern Atlantic Coastal Plain aquifer system	Coastal Plain aquifer systems in semiconsolidated sand	urb	1996	2005	9	27	27	27	29	13	76
linjsus2	LINJ	Long Island-New Jersey Coastal Drainages	Northern Atlantic Coastal Plain aquifer system	Coastal Plain aquifer systems in semiconsolidated sand	sus	1998	2006	8	25	25	24	100	15	10
lirbsus1	LIRB	Lower Illinois River Basin	Glacial aquifer system	Glacial sand and gravel aquifers	sus	1996	2007	11	28	28	29	250	98	0
miselusrc1	MISE	Mississippi Embayment	Alluvial aquifers	Alluvial aquifers	urb	1997	2006	9	20	20	20	48	4	85
necblusrc1	NECB	New England Coastal Basins	Glacial aquifer system	Glacial sand and gravel aquifers	urb	1999	2010	11	21	20	21	25	0	54
nvbrsus2	NVBR	Nevada Basin and Range	Basin and Range basin-fill aquifers	Non-glacial sand and gravel aquifers	sus	1995	2003	8	16	16	16	443	0	64
ozrklusag2a	OZRK	Ozark Plateaus	Ozark Plateaus aquifer system	Carbonate-rock aquifers	ag	1993–95	2007	12	20	20	20	190	85	0
potolusag1	PODL	Potomac River Basin and Delmarva Peninsula	Valley and Ridge carbonate-rock aquifers	Carbonate-rock aquifers	ag	1993	2002	9	24	24	24	148	89	0

Table 1. Description of U.S. Geological Survey National Water-Quality Assessment Program networks analyzed for decadal-scale changes in chloride, dissolved solids, and nitrate in groundwater representing principal aquifers in the United States, 1988–2010.—Continued

[NA, not applicable; Network type: urb = urban land-use study; ag = agricultural land-use study; sus = major aquifer study]

Network name	Study unit code	Study unit name	Principal aquifer[1]	Aquifer rock type[1]	Network type	First full-network sampling event	Second full-network sampling event	Span between sampling (years)	Number of samples			Median well depth, in feet	Land use from 2001[2]	
									Chloride	Dissolved solids	Nitrate		Median percent agricultural land use	Median percent urban land use
pugtluscr1	PUGT	Puget Sound Basin	Puget Sound aquifer system	Glacial sand and gravel aquifers	ag	1997–98	2006	9	18	18	19	28	81	0
pugtlusrs1	PUGT	Puget Sound Basin	Puget Sound aquifer system	Glacial sand and gravel aquifers	urb	1996–97	2005	9	24	23	24	45	1	49
rioglusag1	RIOG	Rio Grande Valley	Rio Grande aquifer system	Non-glacial sand and gravel aquifers	ag	1994	2005	11	25	25	25	20	47	1
riogluscr1	RIOG	Rio Grande Valley	Rio Grande aquifer system	Non-glacial sand and gravel aquifers	ag	1993	2007	14	12	12	12	20	92	0
rioglusrc1	RIOG	Rio Grande Valley	Rio Grande aquifer system	Non-glacial sand and gravel aquifers	urb	1993	2006	13	10	10	10	25	0	97
sacrluscr1	SACR	Sacramento River Basin	Central Valley aquifer system	Non-glacial sand and gravel aquifers	ag	1997	2006	9	21	21	21	35	100	0
sacrlusrc1	SACR	Sacramento River Basin	Central Valley aquifer system	Non-glacial sand and gravel aquifers	urb	1998	2005	7	18	18	18	57	0	74
sacrsus1	SACR	Sacramento River Basin	Central Valley aquifer system	Non-glacial sand and gravel aquifers	sus	1996	2008	12	28	28	28	150	67	4
sanasus2	SANA	Santa Ana Basin	California Coastal Basin aquifers	Non-glacial sand and gravel aquifers	sus	1999	2009	10	14	14	14	926	0	94
sanjluscr1a	SANJ	San Joaquin-Tulare Basins	Central Valley aquifer system	Non-glacial sand and gravel aquifers	ag	1995	2002	7	18	18	18	145	99	0
sanjlusor1a	SANJ	San Joaquin-Tulare Basins	Central Valley aquifer system	Non-glacial sand and gravel aquifers	ag	1993	2001	8	17	17	17	165	96	0
sanjlusor2a	SANJ	San Joaquin-Tulare Basins	Central Valley aquifer system	Non-glacial sand and gravel aquifers	ag	1994	2001	7	19	19	19	135	97	0

Table 1. Description of U.S. Geological Survey National Water-Quality Assessment Program networks analyzed for decadal-scale changes in chloride, dissolved solids, and nitrate in groundwater representing principal aquifers in the United States, 1988–2010.—Continued

[NA, not applicable; Network type: urb = urban land-use study; ag = agricultural land-use study; sus = major aquifer study]

Network name	Study unit code	Study unit name	Principal aquifer[1]	Aquifer rock type[1]	Network type	First full-network sampling event	Second full-network sampling event	Span between sampling (years)	Number of samples			Median well depth, in feet	Land use from 2001[2]	
									Chloride	Dissolved solids	Nitrate		Median percent agricultural land use	Median percent urban land use
sanjsus1	SANJ	San Joaquin-Tulare Basins	Central Valley aquifer system	Non-glacial sand and gravel aquifers	sus	1994	2002	8	26	26	25	171	80	2
santluscr1	SANT	Santee River Basin and Coastal Drainages	Surficial aquifer system	Non-glacial sand and gravel aquifers	ag	1997	2007	10	18	18	19	18	58	0
santlusrc1	SANT	Santee River Basin and Coastal Drainages	Southeastern Coastal Plain aquifer system	Coastal Plain aquifer systems in semiconsolidated sand	urb	1996	2006	10	21	21	17	16	0	81
santsus2	SANT	Santee River Basin and Coastal Drainages	Floridan aquifer system	Carbonate-rock aquifers	sus	1998	2006	8	29	29	29	180	24	0
sctxlusrc1	SCTX	South-Central Texas	Edwards-Trinity aquifer system	Sandstone and carbonate-rock aquifers	urb	1998	2006	8	30	30	30	261	2	37
sctxsus1	SCTX	South-Central Texas	Edwards-Trinity aquifer system	Sandstone and carbonate-rock aquifers	sus	1996	2006	10	23	22	23	328	24	0
sofllusor1	SOFL	Southern Florida	Surficial aquifer system	Non-glacial sand and gravel aquifers	ag	1998	2009	11	18	18	17	13	74	0
sofllusrc1a	SOFL	Southern Florida	Biscayne aquifer	Carbonate-rock aquifers	urb	1996–97	2010	14	13	13	17	15	2	89
spltluscr1	SPLT	South Platte River Basin	Alluvial aquifers	Alluvial aquifers	ag	1994	2002	8	29	29	29	23	67	0
trinsus3	TRIN	Trinity River Basin	Coastal lowlands aquifer system	Coastal Plain aquifer systems in semiconsolidated sand	sus	1994	2002	8	17	17	16	180	25	7
ucollusrc1	UCOL	Upper Colorado River Basin	Alluvial aquifers	Alluvial aquifers	urb	1997	2010	13	15	15	16	23	13	44
uirblusrc1	UIRB	Upper Illinois River Basin	Glacial aquifer system	Glacial sand and gravel aquifers	urb	2000	2010	10	18	18	18	28	21	67

Table 1. Description of U.S. Geological Survey National Water-Quality Assessment Program networks analyzed for decadal-scale changes in chloride, dissolved solids, and nitrate in groundwater representing principal aquifers in the United States, 1988–2010.—Continued

[NA, not applicable; Network type: urb = urban land-use study; ag = agricultural land-use study; sus = major aquifer study]

Network name	Study unit code	Study unit name	Principal aquifer[1]	Aquifer rock type[1]	Network type	First full-network sampling event	Second full-network sampling event	Span between sampling (years)	Number of samples: Chloride	Number of samples: Dissolved solids	Number of samples: Nitrate	Median well depth, in feet	Land use from 2001[2]: Median percent agricultural land use	Land use from 2001[2]: Median percent urban land use
umisluscr1	UMIS	Upper Mississippi River Basin	Glacial aquifer system	Glacial sand and gravel aquifers	ag	1998	2006	8	22	22	22	23	62	0
umislusrc1	UMIS	Upper Mississippi River Basin	Glacial aquifer system	Glacial sand and gravel aquifers	urb	1996	2006	10	26	26	26	19	0	87
umissus3	UMIS	Upper Mississippi River Basin	Cambrian-Ordovician aquifer system	Sandstone aquifers	sus	1996	2007	11	22	22	22	162	79	0
usnkluscr2	USNK	Upper Snake River Basin	Snake River Plain basaltic-rock aquifers	Igneous and metamorphic-rock aquifers	ag	1993	2005	12	26	26	26	230	99	0
usnkluscr3	USNK	Upper Snake River Basin	Snake River Plain basaltic-rock aquifers	Igneous and metamorphic-rock aquifers	ag	1994	2005	11	28	28	28	195	95	0
whitluscr1	WHMI	White and Great and Little Miami River Basins	Glacial aquifer system	Glacial sand and gravel aquifers	ag	1994	2002	8	20	20	20	27	98	0
willlusag3	WILL	Willamette Basin	Willamette Lowland basin-fill aquifers	Non-glacial sand and gravel aquifers	ag	1993	2002	9	24	24	24	60	80	14
wmiclusag2	WMIC	Western Lake Michigan Drainages	Glacial aquifer system	Glacial sand and gravel aquifers	ag	1994	2002	8	26	26	26	42	77	0
wmicsus1	WMIC	Western Lake Michigan Drainages	Cambrian-Ordovician aquifer system	Sandstone aquifers	sus	1995	2002	7	25	25	25	179	53	1

[1] Principal aquifers from U.S. Geological Survey (2003); Information on alluvial aquifers is from Maupin and Barber (2005).

[2] Land use data from Homer and others (2001). Agricultural land = sum of row crop, hay and pasture, small grains, and fallow land. Urban = sum of low intensity residential, high-intensity residential, commercial, industrial, and transportation.

Table 6. Decadal-scale changes in chloride concentrations in groundwater in U.S. Geological Survey National Water-Quality Assessment Program well networks in the United States, 1988–2010, based on time-series analysis of the biennial data set.

[**Bold** indicates tau value is statistically significant, **(+)**, indicates significant increase in concentration at the 90-percent confidence level; **(–)**, indicates significant decrease in concentration at the 90-percent confidence level; <, less than]

Network name	tau value from Regional Kendall test	Statistically significant result	Probability value from Regional Kendall test	Years of record	Number of sites	Begining year	Ending year	Annual change in chloride concentration, in milligrams per liter
acfbluscr3	**0.39**	(+)	**0.019**	17	5	1993	2009	**0.04**
acfbsus1	**0.57**	(+)	**0.004**	15	5	1995	2009	**0.05**
albelusag1	0.35		0.125	14	5	1994	2007	0.50
cazbsus1a	0.20		0.324	13	5	1996	2008	0.20
ccptlusag2b	**-0.41**	(–)	**0.002**	16	5	1993	2008	**-0.66**
ccptlusor1b	**-0.64**	(–)	**<.001**	17	5	1994	2010	**-0.97**
ccptsus1b	0.08		0.742	15	5	1994	2008	0.02
dlmvluscr1	-0.04		0.908	22	5	1988	2009	-0.03
dlmvsus1	**0.35**	(+)	**0.084**	22	5	1988	2009	**0.06**
eiwaluscr1	0.13		0.565	13	5	1997	2009	0.05
eiwasus2	-0.08		0.787	12	4	1998	2009	-0.02
lerilusrc1	**0.60**	(+)	**0.002**	13	5	1996	2008	**4.3**
lerisus1	**0.56**	(+)	**0.003**	12	5	1998	2009	**0.17**
linjlusrc1	**0.55**	(+)	**<.001**	14	5	1996	2009	**2.2**
linjsus2	**0.49**	(+)	**0.005**	12	5	1998	2009	**0.82**
lirbsus1	-0.01		1.00	14	5	1996	2009	0.00
miselusrc1	**-0.31**	(–)	**0.065**	13	5	1997	2009	**-0.32**
necblusrc1	0.24		0.228	11	5	1999	2009	1.4
nvbrsus2	**0.39**	(+)	**0.020**	24	6	1987	2010	**0.05**
ozrklusag2a	0.00		1.00	15	5	1995	2009	0.00
potolusag1	**0.45**	(+)	**<.001**	17	6	1993	2009	**0.24**
pugtluscr1	**-0.30**	(–)	**0.100**	12	5	1997	2008	**-0.13**
pugtlusrs1	0.11		0.414	13	5	1996	2008	0.03
rioglusag1	0.27		0.165	17	4	1994	2010	0.92
riogluscr1	0.13		0.475	16	5	1993	2008	0.00
rioglusrc1	-0.10		0.715	18	5	1993	2010	0.08
sacrluscr1	0.08		0.742	12	5	1997	2008	0.16
sacrlusrc1	-0.09		0.661	11	5	1998	2008	-0.24
sanasus2	-0.02		1.00	12	5	1999	2010	-0.05
sanjluscr1a	**0.29**	(+)	**0.082**	24	5	1987	2010	**0.32**
sanjlusor1a	**0.31**	(+)	**0.027**	18	5	1993	2010	**0.38**
sanjlusor2a	**0.50**	(+)	**0.005**	15	5	1994	2008	**0.21**
sanjsus1	0.05		0.799	23	6	1986	2008	0.05

Table 6. Decadal-scale changes in chloride concentrations in groundwater in U.S. Geological Survey National Water-Quality Assessment Program well networks in the United States, 1988–2010, based on time-series analysis of the biennial data set.—Continued

[**Bold** indicates tau value is statistically significant, **(+)**, indicates significant increase in concentration at the 90-percent confidence level; **(–)**, indicates significant decrease in concentration at the 90-percent confidence level; <, less than]

Network name	tau value from Regional Kendall test	Statistically significant result	Probability value from Regional Kendall test	Years of record	Number of sites	Begining year	Ending year	Annual change in chloride concentration, in milligrams per liter
santlusrc1	**0.49**	(+)	**0.010**	14	4	1996	2009	**0.19**
santsus2	0.02		1.00	12	5	1998	2009	0.01
sctxlusrc1	**0.29**	(+)	**0.031**	11	5	1998	2008	**0.23**
sctxsus1	0.11		0.539	14	5	1996	2009	0.04
sofllusor1	0.00		1.00	12	5	1998	2009	0.16
sofllusrc1a	**0.32**	(+)	**0.018**	15	5	1996	2010	**0.97**
spltluscr1	**0.42**	(+)	**0.036**	17	5	1992	2008	**1.9**
trinsus3	0.16		0.516	16	5	1994	2009	0.14
ucollusrc1	-0.05		0.858	15	4	1996	2010	-0.12
uirblusrc1	**0.65**	(+)	**<0.001**	11	5	2000	2010	**22**
umisluscr1	0.06		0.786	12	5	1998	2009	0.03
umislusrc1	0.06		0.669	14	5	1996	2009	0.33
umissus3	0.24		0.273	14	5	1996	2009	0.05
usnkluscr2	-0.19		0.230	18	7	1993	2010	-0.19
usnkluscr3	**-0.42**	(–)	**0.011**	17	5	1994	2010	**-0.10**
whitluscr1	-0.32		0.100	16	5	1994	2009	-0.30
[1]willlusag3	0.23		0.188	18	5	1993	2010	0.02
wmiclusag2	**-0.36**	(–)	**0.063**	16	5	1994	2009	**-0.23**
wmicsus1	0.26		0.205	15	5	1995	2009	0.03

[1]Data from willlusag3 and willlusag2 networks were combined for biennial analysis.

Table 7. Decadal-scale changes in dissolved solids concentrations in groundwater in U.S. Geological Survey National Water-Quality Assessment Program well networks in the United States, 1988–2010, based on time-series analysis of the biennial data set.

[**Bold** indicates tau value is statistically significant, **(+)**, indicates significant increase in concentration at the 90-percent confidence level; **(–)**, indicates significant decrease in concentration at the 90-percent confidence level; <, less than]

Network name	tau value from Regional Kendall test	Statistically significant result	Probability value from Regional Kendall test	Years of record	Number of sites	Begining year	Ending year	Annual change in dissolved solids concentration, in milligrams per liter
acfbluscr3	**0.41**	(+)	**0.012**	17	5	1993	2009	**1.4**
acfbsus1	**0.52**	(+)	**0.008**	15	5	1995	2009	**1.4**
albelusag1	0.12		0.675	14	5	1994	2007	0.46
cazbsus1a	0.08		0.742	13	5	1996	2008	1.5
ccptlusag2b	-0.16		0.245	16	5	1993	2008	-3.0
ccptlusor1b	**-0.56**	(–)	**0.002**	17	5	1994	2010	**-7.5**
ccptsus1b	**0.36**	(+)	**0.063**	15	5	1994	2008	**1.3**
eiwaluscr1	-0.22		0.300	13	5	1997	2009	-2.7
eiwasus2	**-0.39**	(–)	**0.090**	12	4	1998	2009	**-2.3**
lerilusrc1	**0.64**	(+)	**0.001**	13	5	1996	2008	**10**
lerisus1	0.08		0.742	12	5	1998	2009	0.24
linjlusrc1	**0.49**	(+)	**<0.001**	14	5	1996	2009	**4.5**
linjsus2	0.24		0.175	12	5	1998	2009	1.3
lirbsus1	0.01		1.00	14	5	1996	2009	0.05
miselusrc1	**-0.28**	(–)	**0.093**	13	5	1997	2009	**-1.7**
necblusrc1	0.32		0.153	11	5	1999	2009	1.7
nvbrsus2	0.30		0.109	16	6	1995	2010	0.70
ozrklusag2a	0.24		0.228	15	5	1995	2009	1.5
potolusag1	0.16		0.262	17	6	1993	2009	0.64
pugtluscr1	**-0.33**	(–)	**0.066**	12	5	1997	2008	**-2.9**
pugtlusrs1	0.20		0.112	13	5	1996	2008	1.2
rioglusag1	0.24		0.234	17	4	1994	2010	13
riogluscr1	0.10		0.605	16	5	1993	2008	1.1
rioglusrc1	-0.16		0.516	18	5	1993	2010	-3.8
sacrluscr1	**0.44**	(+)	**0.021**	12	5	1997	2008	**9.9**
sacrlusrc1	0.17		0.335	11	5	1998	2008	1.8
sanasus2	-0.12		0.553	12	5	1999	2010	-0.81
sanjluscr1a	**0.69**	(+)	**<0.001**	16	5	1995	2010	**7.4**
sanjlusor1a	**0.36**	(+)	**0.010**	18	5	1993	2010	**5.0**
sanjlusor2a	**0.50**	(+)	**0.005**	15	5	1994	2008	**4.6**
sanjsus1	0.27		0.177	14	6	1995	2008	1.9
santlusrc1	0.06		0.843	14	4	1996	2009	0.65
santsus2	-0.26		0.141	12	5	1998	2009	-1.6

Table 7. Decadal-scale changes in dissolved solids concentrations in groundwater in U.S. Geological Survey National Water-Quality Assessment Program well networks in the United States, 1988–2010, based on time-series analysis of the biennial data set.—Continued

[**Bold** indicates tau value is statistically significant, **(+)**, indicates significant increase in concentration at the 90-percent confidence level; **(–)**, indicates significant decrease in concentration at the 90-percent confidence level; <, less than]

Network name	tau value from Regional Kendall test	Statistically significant result	Probability value from Regional Kendall test	Years of record	Number of sites	Begining year	Ending year	Annual change in dissolved solids concentration, in milligrams per liter
sctxlusrc1	**0.29**	(+)	**0.031**	11	5	1998	2008	**2.7**
sctxsus1	0.09		0.661	14	5	1996	2009	0.20
sofllusor1	0.33		0.113	12	5	1998	2009	5.0
sofllusrc1a	**0.25**	(+)	**0.066**	15	5	1996	2010	**3.4**
spltluscr1	-0.13		0.581	17	5	1992	2008	-13
trinsus3	**0.58**	(+)	**0.006**	16	5	1994	2009	**1.4**
ucollusrc1	**0.33**	(+)	**0.086**	15	4	1996	2010	**4.4**
uirblusrc1	**0.65**	(+)	**<0.001**	11	5	2000	2010	**33**
umisluscr1	0.18		0.319	12	5	1998	2009	6.5
umislusrc1	0.00		1.00	14	5	1996	2009	<.01
umissus3	**0.38**	(+)	**0.068**	14	5	1996	2009	**1.8**
usnkluscr2	0.19		0.230	18	7	1993	2010	1.3
usnkluscr3	-0.04		0.874	17	5	1994	2010	-0.05
whitluscr1	-0.08		0.742	16	5	1994	2009	-1.1
[1]willlusag3	**0.49**	(+)	**0.004**	18	5	1993	2010	**1.3**
wmiclusag2	0.00		1.00	16	5	1994	2009	-0.36
wmicsus1	**0.35**	(+)	**0.084**	15	5	1995	2009	**1.3**

[1]Data from willlusag3 and willlusag2 networks were combined for biennial analysis.

Table 8. Decadal-scale changes in nitrate concentrations in groundwater in U.S. Geological Survey National Water-Quality Assessment Program well networks in the United States, 1988–2010, based on time-series analysis of the biennial data set.

[**Bold** indicates tau value is statistically significant; **(+)**, indicates significant increase in concentration at the 90-percent confidence level; **(–)**, indicates significant decrease in concentration at the 90-percent confidence level; N, nitrogen; <, less than]

Network name	tau value from Regional Kendall test	Statistically significant result	Probability value from Regional Kendall test	Years of record	Number of sites	Begining year	Ending year	Annual change in nitrate, in milligrams per liter as N
acfbluscr3	**0.40**	(+)	**0.005**	17	5	1993	2009	**0.04**
acfbsus1	**0.57**	(+)	**0.004**	15	5	1995	2009	**0.03**
albelusag1	-0.06		0.843	14	5	1994	2007	<.01
cazbsus1a	0.20		0.324	13	5	1996	2008	0.01
ccptlusag2b	-0.16		0.176	18	5	1993	2010	-0.17
ccptlusor1b	**-0.47**	(–)	**0.004**	17	5	1994	2010	**-0.15**
ccptsus1b	-0.09		0.614	17	5	1994	2010	-0.01
dlmvluscr1	0.26		0.178	22	5	1988	2009	<.01
dlmvsus1	0.12		0.551	22	5	1988	2009	<.01
eiwalsus2	-0.19		0.271	12	4	1998	2009	<.01
eiwaluscr1	-0.15		0.450	13	5	1997	2009	<.01
lerilusrc1	0.20		0.270	13	5	1996	2008	0.01
lerisus1	**-0.14**	(–)	**0.096**	12	5	1998	2009	**<.01**
linjlusrc1	**0.22**	(+)	**0.069**	14	5	1996	2009	**0.02**
linjsus2	0.15		0.381	12	5	1998	2009	<.01
lirbsus1	-0.10		0.314	14	5	1996	2009	<.01
miselusrc1	0.12		0.450	13	5	1997	2009	<.01
necblusrc1	0.02		1.00	12	5	1999	2010	<.01
nvbrsus2	**0.34**	(+)	**0.054**	23	6	1988	2010	**0.01**
ozrklusag2a	-0.16		0.443	15	5	1995	2009	-0.01
potolusag1	**0.31**	(+)	**0.021**	17	6	1993	2009	**0.04**
pugtluscr1	**-0.42**	(–)	**0.015**	12	5	1997	2008	**-0.42**
pugtlusrs1	**0.22**	(+)	**0.076**	13	5	1996	2008	**0.05**
rioglusag1	-0.02		1.00	17	4	1994	2010	<.01
riogluscr1	**-0.30**	(–)	**0.046**	18	5	1993	2010	**-0.01**
rioglusrc1	-0.07		0.728	18	5	1993	2010	<.01
sacrluscr1	-0.17		0.283	14	5	1997	2010	<.01
sacrlusrc1	0.22		0.270	11	5	1998	2008	-0.03
sanasus2	-0.30		0.114	12	5	1999	2010	-0.02
sanjluscr1a	**0.71**	(+)	**<0.001**	24	5	1987	2010	**0.28**
sanjlusor1	**0.37**	(+)	**0.008**	18	5	1993	2010	**0.13**
sanjlusor2	**0.33**	(+)	**0.034**	17	5	1994	2010	**0.25**
sanjsus1	**0.47**	(+)	**0.003**	23	6	1986	2008	**0.08**
santlusrc1	-0.07		0.690	14	4	1996	2009	<.01

Table 8. Decadal-scale changes in nitrate concentrations in groundwater in U.S. Geological Survey National Water-Quality Assessment Program well networks in the United States, 1988–2010, based on time-series analysis of the biennial data set.—Continued

[**Bold** indicates tau value is statistically significant; **(+)**, indicates significant increase in concentration at the 90-percent confidence level; **(–)**, indicates significant decrease in concentration at the 90-percent confidence level; N, nitrogen; <, less than]

Network name	tau value from Regional Kendall test	Statistically significant result	Probability value from Regional Kendall test	Years of record	Number of sites	Begining year	Ending year	Annual change in nitrate, in milligrams per liter as N
santsus2	**-0.20**	(–)	**0.023**	12	5	1998	2009	**<.01**
sctxlusrc1	0.03		0.868	11	5	1998	2008	0.01
sctxsus1	0.03		0.868	11	5	1998	2008	0.01
sofllusor1	-0.08		0.621	12	5	1998	2009	<.01
sofllusrc1a	-0.01		1.00	15	5	1996	2010	<.01
spltluscr1	-0.19		0.269	19	5	1992	2010	-0.12
trinsus3	0.16		0.230	16	5	1994	2009	<.01
ucollusrc1	0.15		0.435	15	4	1996	2010	0.02
uirblusrc1	0.20		0.152	11	5	2000	2010	<.01
umisluscr1	0.14		0.430	12	5	1998	2009	0.02
umislusrc1	**0.32**	(+)	**0.013**	14	5	1996	2009	**0.16**
umissus3	-0.09		0.671	14	5	1996	2009	<.01
usnkluscr2	**0.37**	(+)	**0.002**	18	7	1993	2010	**0.03**
usnkluscr3	**0.62**	(+)	**<0.001**	17	5	1994	2010	**0.01**
whitluscr1	-0.16		0.225	16	5	1994	2009	<.01
[1]willlusag3	-0.09		0.468	18	5	1993	2010	<.01
wmiclusag2	**-0.36**	(–)	**0.049**	16	5	1994	2009	**-0.15**
wmicsus1	0.09		0.551	15	5	1995	2009	<.01

[1]Data from willlusag3 and willlusag2 networks were combined for biennial analysis.

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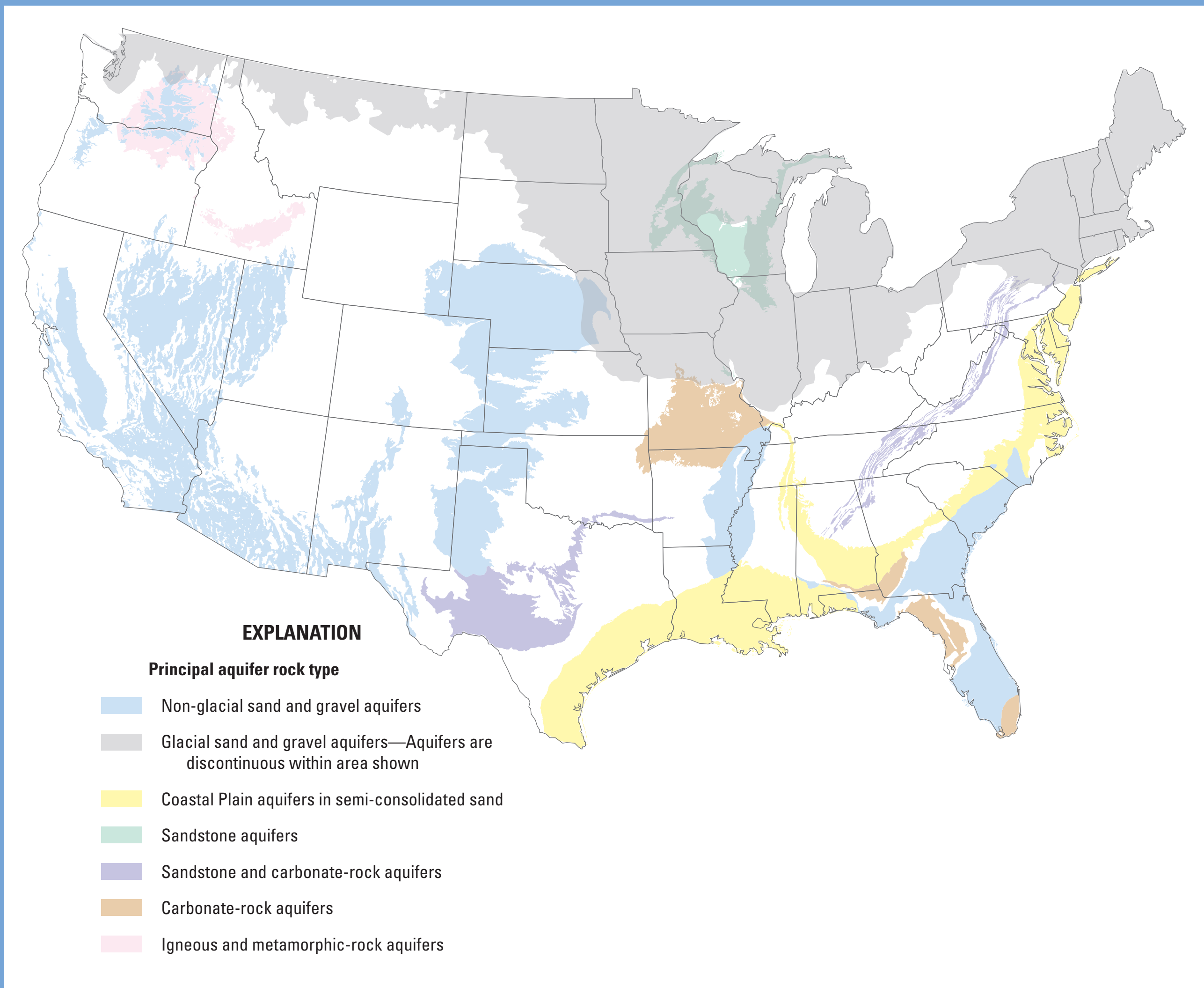

Lindsey and Rupert—**Methods for Evaluating Groundwater Quality Data and Decadal-Scale Changes in the United States, 1988–2010**—Scientific Investigations Report 2012–5049